Capio Lumen

PRACTICAL TUNNELLING

PRINTED BY
SPOTTISWOODE AND CO., NEW-STREET SQUARE
LONDON

PRACTICAL TUNNELLING

BY

FREDK. WALTER SIMMS

F.G.S. M.INST.C.E.

FOURTH EDITION, REVISED AND GREATLY EXTENDED

WITH ADDITIONAL CHAPTERS ILLUSTRATING RECENT PRACTICE

BY

D. KINNEAR CLARK

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With Thirty-six Plates and other Illustrations

NEW YORK

D. VAN NOSTRAND COMPANY

23 MURRAY AND 27 WARREN STREETS

1896

PREFACE TO FOURTH EDITION.

EIGHTEEN years have elapsed since the last edition of this work was published. The construction of numerous tunnels has necessarily accompanied the vast extensions of railway systems which have been made during the period under review, in all parts of the civilised world; and the employment of subways—subterranean and subaqueous—is being largely resorted to for the purpose of facilitating the means of access and communication within the areas of thickly populated towns and cities. The requirements of modern sanitation demand, and have in many cases obtained, a purer and more ample supply of water for the use of urban populations. The sources of supply being not infrequently remote from the points of distribution and consumption, the construction of aqueducts of great length and of considerable size has been obligatory. An immense mass of information cognate to the subject matter of this book is therefore at disposal, and to deal with the whole of this, even in the most cursory manner, would far exceed the limits assigned for the purpose. It has, therefore, been necessary to exclude from consideration much valuable and interesting material which, if space permitted, was well deserving of mention and record. In making a selection, I have endeavoured, as far as possible,

to describe those projects which, either on account of the magnitude of the interests served or of the natural or other difficulties to be surmounted, appeared to me to be most deserving of notice, and as representative as possible of modern engineering practice in this connection.

An exception to this system of selection has been made in the case of the St. Gothard Tunnel, which has been open for traffic since January 1882. The history of the earlier portion of this great work having been described in the last edition of this book, it has been thought desirable to complete the narrative. The description has therefore been continued in the first new chapter of the present edition (Chapter XXVII.). This chapter also contains an account of the subsequent widening of the tunnel—an operation which, on account of the narrowness of the original perforation, was carried out under serious difficulties, owing to the necessity that existed of not interfering with the traffic.

As regards water projects, the aqueducts which supply the important cities of Liverpool and Glasgow, and which derive their supply from Lake Vyrnwy and Loch Katrine respectively, have been chosen. The new Glasgow waterworks scheme is in supersession of the original one, which has been described in an earlier edition of the book, and which has been found to be inadequate for the increased requirements of the city.

A notable undertaking of this description, possibly the most extensive and important of its kind ever contemplated, is that recently put forward by the London County Council, having for its object to provide the Metropolis with a copious supply of pure soft water from the head waters of the rivers Usk, Wye, Tawey, in South Wales. Should this scheme ever, in the fulness of time, be brought

to maturity, many years must elapse before the work becomes an accomplished fact; and the details may, therefore, be left to be described fully in a future edition of this work. It will be sufficient for present purposes to mention that the scheme involves the construction of a double aqueduct having a united length of some four hundred and fifty miles; and that it will include, *inter alia*, the construction of several tunnels of great length. The total cost of the undertaking is estimated at 39,000,000*l.*; and it is calculated that the conduits will deliver to the two service reservoirs—which are to be situated at Boreham Wood, near Watford, and at Banstead (Surrey), respectively—a daily supply of at least four hundred and fifteen millions of gallons of water. This would be equal to about twice the present-day requirements of the Metropolis, or more than sufficient for the estimated consumption fifty years hence.

In connection with railway tunnelling, the mighty masses of the Alps have been penetrated by a third tunnel—the Arlberg, whilst a fourth—the Simplon, is now in course of construction. The proposed methods of driving the headings for this latter tunnel, and the means of ventilating them, are briefly described in the text.

The question of the ventilation of long tunnels has received additional attention. The difficulty attendant upon the disposal of the products of combustion within the area of crowded cities, except by the use of costly and unsightly chimneys, still remains; and the 'blow-holes' constructed some years ago by the District Railway (London) to assist in the ventilation of their tunnels, several of which had to be closed owing to the nuisance caused by the escape of the noxious fumes, are probably well remembered by many

residents in the Metropolis.[1] It may be added that the openings made in the crown of the St. Louis Tunnel (U.S.A.) for a similar purpose had also to be closed for the same reason, and the additional one—that they were ineffective. The introduction of electricity as a motive power, and the success which the City and South London Railway have obtained by the use of electric motors, have possibly given a lead which other underground railways may in time follow; and, as a matter of fact, at the time of writing, the Bills of two companies, which purpose using electricity as a tractive power, have recently received Parliamentary sanction. Reference is here made to the Central London Railway and the Waterloo and City Railway; whilst a third rival line of the last mentioned is threatened. The whole of these lines will be underground throughout. The termini of the Central London Railway will be near Shepherd's Bush and the Mansion House respectively; and those of the Waterloo and City Railway at the points indicated by the title of the line. Considerable progress has already been made with the subaqueous tunnel on the last-mentioned line, which passes under the Thames bed close to and on the western side of Blackfriars Bridge.

Whilst dealing with the subject of ventilation of tunnels, reference may here be made to the novel scheme to be adopted in the ventilation of the Simplon Tunnel, previously alluded to. There will be two tunnels, connected at intervals by transverse passages. Whilst under construction, air will be forced into tunnel No. 1 and through the passages into No. 2, whence it will escape into the atmosphere. When the tunnels are

[1] From a statement recently made in the House of Commons by the Secretary to the Local Government Board, it appears that the Government have no powers to compel efficient ventilation of tunnels. It is therefore probable that the end of the present unsatisfactory condition of affairs has not yet been reached.

finished, fans will be placed at the entrances to the two tunnels at which the up and down trains respectively enter, and a volume of air driven into each in the direction of the train's motion. The tunnel when completed will be twelve miles long, but by keeping the ends of the tunnels at which the air is introduced closed by means of doors, and with the assistance of the trains, it is anticipated that a sufficient current of pure air will pass throughout the entire length of both tunnels.

There has been a remarkable immunity from accidents of a serious character to completed tunnels, during the period under review, and the subject, therefore, requires but passing reference. Having regard to the destructive action to which structures of this character are liable, through the action of water and the constant vibration caused by passing trains, this circumstance is a high testimony to the strength and solidity of the tunnels, and to the vigilance which has enabled small defects to be detected and rectified before attaining serious importance.

The one exception, which in this case proves the rule, is the collapse of the St. Katherine Tunnel near Guildford, on the London and South-Western Railway, on March 3, 1895. The accident was fortunately unattended by fatal consequences, and was found on subsequent inquiry to be due to the action of water which had percolated through from the drains of a house situated on the hill, above the point where the tunnel gave way. It appeared that the water had caused a cavity above the crown of the tunnel, and had, moreover, entirely rotted some timbers which had been improperly built in, instead of being removed when the tunnel was made, and had thus weakened the arch to the extent of one ring of brickwork. The tunnel was an old one, having been built about 1849; it will probably be either rebuilt throughout or relined.

Reference is made in the text to an invention which was tried with successful results in the construction of the new King's Cross Tunnel, and which, owing to the saving in labour and material, is likely to some extent to supersede the old method of timbering the headings previous to the introduction of the masonry walls.

I have again to express my indebtedness to the inexhaustible pages of the *Minutes of Proceedings of the Institution of Civil Engineers* for much valuable information, and to the proprietors of the *Engineer* and *Engineering* journals for the descriptions of some of the tunnels which appear in these pages, as well as for the drawings and diagrams referred to therein.

D. K. C.

LONDON: *December* 1895.

PUBLISHERS' NOTE.

The Publishers deeply regret to record the Death of Mr. D. K. Clark on January 22, 1896, within a few days of his passing for press a proof of the foregoing Preface. In the necessity which then arose of completing the revision of the proof sheets of the new chapters added to the present edition by Mr. Clark, the Publishers have had the advantage of the assistance of Mr. Maurice Fitzmaurice, M.Inst.C.E., to whom their very cordial acknowledgments are due.

April 1896.

PREFACE TO THIRD EDITION.

THE elaborate account of the construction of the Blechingley and the Saltwood Tunnels, on the South-Eastern Railway, which constitutes the original work of Mr. Simms, comprises a thoroughly practical description of the work at every stage of its progress, and presents in a typical form the ordinary routine and experience of tunnelling in clay and in sand. As a monograph in tunnelling Mr. Simms's work stands unrivalled; and it is as useful now as it was on the day it was first published. At the same time, since those tunnels were completed, a great deal of valuable experience has been accumulated in tunnelling; for many other tunnels have been constructed, under different circumstances, and through ground of various geological formation. Other types of construction have been developed, of which it is scarcely necessary to state that the tunnel under the Col de Fréjus, commonly known as the Mont Cenis Tunnel, above 7½ miles in length, is the greatest and most wonderful achievement of the time. The engineering construction of the Metropolitan Railway, popularly known as the Underground Railway, in London, is a unique performance, which most men pronounced impossible before the event, and this great work is only less admirable than the Mont Cenis Tunnel. Every tunnel has its own peculiar history: in execution, difficulties are continually

occurring which cannot be foreseen in the estimates; contingencies are met with which require all the resources of mechanical science, and all the experience and enterprise of engineers and contractors, to bring the work to a successful issue.

This, the third edition of Simms's work, is opened with an introductory chapter. The text of the original work is substantially retained in matter and in form; except that the statistical matter bearing upon labour, materials, wages, and cost of construction, which was in the previous edition scattered throughout the text, has been drafted off and collected into a special chapter, forming the conclusion of the original text. The supplementary portion of the work is devoted to an elucidation of the later developments of tunnelling practice. The systems of driving tunnels, known on the Continent as the English and the Belgian systems—based on the bottom heading and the top heading respectively—are investigated in an early chapter. Then follows a discussion of the ordinary casualties in tunnelling: a subject full of interest and of usefulness to those who have to grapple with the unforeseen. Then there is some of the experience of tunnelling in clay, marl, &c., in coal formations and in hard rock. The construction of the Mont Cenis Tunnel is elaborately detailed in an account for which the information was chiefly derived from two papers read by Mr. Thomas Sopwith before the Institution of Civil Engineers, with the discussions thereupon. The St. Gothard Tunnel, now in course of construction, which will, when completed, have a length of 9¼ miles, has likewise received elaborate treatment, the materials for which have, for the most part, been drawn from the excellently prepared quarterly reports of the engineer. Much space has been given to the details of labour, prices, and cost of construction.

In view of the entirely new conditions initiated within the last few years—dense traffic, and great length of tunnels—efficient ventilation has come to the front as a factor in tunnel-engineering. That subject has therefore been treated herein at some length, and the principles enunciated are readily applicable for securing the ventilation of tunnels with efficiency and with economy.

A comprehensive Index, with Tables of Contents, have been prepared for this edition, and a Glossary of Terms peculiar to mining and tunnelling is added.

The Editor acknowledges the assistance he has derived from the *Minutes of Proceedings of the Institution of Civil Engineers*, that inexhaustible mine of engineering knowledge and experience. He has, by permission of the Council of the Institution, drawn from those volumes the materials for describing, detailing, and illustrating several important tunnels: viz. the Buckhorn Weston, Lydgate, Netherton, Stapleton, Lindal, and Mont Cenis. He is also indebted to Mr. C. B. Lane for additional particulars of materials, labour, and cost of the enlargement of Stapleton Tunnel; to Mr. Stileman for drawings illustrative of the Netherton Tunnel; and to Mr. J. G. Morrison for particulars of the Clifton Tunnel.

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PRACTICAL TUNNELLING.

INTRODUCTORY CHAPTER.

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SUBTERRANEAN TUNNELS were introduced for the first time, probably, in works for inland navigation. The tunnel on the Languedoc Canal, commenced in 1666, was one of the earliest instances of this description of work. The Hartshill Tunnel, on the Chesterfield Canal, 3,000 yards long, and the Sapperton Tunnel, on the Thames and Severn Navigation, 2½ miles long, and lined with masonry, are among the earliest constructions in England. Tunnels were also constructed for the Duke of Bridgwater's Canal, some miles of which, at Worsley, are made underground; also at Harecastle, by Brindley, on the Trent and Mersey Canal, in 1776, which was rendered more convenient by Telford in 1826 by the addition of another tunnel parallel to it, of larger dimensions. In the Huddersfield Canal, also, there is a tunnel 3 miles long; and there is the Bramston Tunnel, on the Grand Junction Canal. The Dudley Tunnel, on the Birmingham Canal, is 3,200 yards in length, or six-tenths of a mile. In the portions lined with brickwork it is about 8 feet wide, and it is 6 feet high above the water-level.

It must be admitted that the *crux* of engineers, the tunnel under the Thames, at Rotherhithe, surpassed all other tunnels of the time for magnitude, boldness of design, and ingenuity in the means of construction, as well as for the extraordinary difficulties by which the work was attended. It will remain a lasting monument of the talents and perseverance of Sir Isambard

Brunel, the engineer by whom it was designed and constructed. It was commenced in the year 1825; but the progress of the work was suspended for seven years for want of funds, and was at length resumed with the aid of a Treasury loan. It consisted of two arched openings, 1,200 feet in length, of 13 feet 9 inches span each, 16 feet 4 inches high from the invert to the soffit of the arch, separated from each other by a pier 4 feet thick, having sixty-four lateral arches, of 4 feet span, to communicate between the main openings or galleries, the whole being surrounded with massive brickwork, built to a rectangular section, measuring over all 38 feet wide, and 22 feet high. The crown of the tunnel is about 16 feet below the bed of the river. The work of excavation was conducted by means of an immense framing of cast iron, which Mr. Brunel called a shield, weighing 120 tons, and sufficiently large to embrace the whole width and height of the intended structure. The shield was divided into thirty-six compartments, each sufficiently large for a man to work in within and behind the shield, yet capable of being closed to prevent the access of water when required. The shield was moved forward by means of horizontal screws, which had their bearings on the brickwork behind, as it was finished. Upon the moving stage which followed the shield the materials for construction were placed, and the soil thrown. This contrivance was perfectly successful; and though two irruptions from the river took place, the apertures were effectually stopped by heaving bags of clay into the holes in the bottom of the river, and covering them over with tarpauling, with a stratum of gravel over all. The work proceeded for several months at the rate of 2 feet in twenty-four hours, displacing from 90 to 100 tons of earth. For each foot of advance 5,500 bricks were required, and of course double this number was used every day; they were laid in Roman cement, and the tunnel was lined with the same material. A hundred men were constantly employed. The approaches at each end consisted of a vertical shaft, 50 feet in diameter, and 80 feet deep, below the surface of the streets. The tunnel was finally completed, at a cost of 1,137*l.* per lineal yard, and was opened to the public in 1843. It has recently been converted into a railway tunnel, with a line of rails in each gallery, forming a portion of the East London Railway.

It was reserved for the exigencies of railway construction to develop the science and the practice of tunnelling; for railway tunnels far surpass, both in length and in sectional dimensions, the tunnels previously required in the construction of canals.

It is a rule which is generally applicable, in the construction of railways or canals, that where a cutting would have a vertical depth of more than 60 feet it would be costlier to make an open cutting than to 'bore,' unless the material is required for a neighbouring embankment. Economy is the principal test in these questions; for a tunnel may be made of any length, and through any substance, from granite rock to quicksand. In materials of rigid and unyielding character, such as rock and chalk, the practical limit to the depth of a cutting goes far beyond that point at which a tunnel would be more economical. In such materials, it is to be remarked, it does not become necessary to augment the inclination of the slopes with an increase of the depth of cutting. In soils of a yielding character, on the contrary, such augmented inclination is necessary, and it becomes more necessary in proportion as the rigidity is diminished, for a yielding soil is not sufficiently tenacious to support its own weight except over a widely spread base. In view of such conditions, it is easily understood that the cost of cuttings increases in a highly accelerated ratio with the depth; and, as a matter of fact, gravel or sand will not, in general, permit, with perfect safety, a cutting much over from 70 to 80 feet in depth; and in clay the limits are much more contracted.

The method of proceeding with tunnelling depends upon the kind of material to be excavated. The nature of the material is, in ordinary circumstances, ascertained approximately by means of borings and trial shafts, which are sunk from the surface over the axial line of the tunnel to be constructed, through the intervening strata, to the level of the lower part of the tunnel. Particular attention is required to be given to the practical geology of the material, whether rock, earth, chalk, or sand; and the skill of the engineer and the contractor is tested by the application of their knowledge of the subject to the development of safe and proper forms and proportions, as well as to the execution of the necessary works of construction. All unstratified rocks which are homogeneous and free from

faults may be excavated so as to leave the sides of the excavation vertical, or nearly so, and thus a tunnel may be formed by merely driving a heading through the rock, without the protection of an arch of masonry. It is generally only in such strata as clay-slate, granite, or other primary rock, that works can be left without artificial protection. On the line of the Tavistock Canal, a tunnel of 1¾ mile in length, driven many years since through clay-slate and granite, has stood perfectly well without any internal arching. In gneissous formations, the walls of excavations may stand and endure unprotected, whilst it may be judicious, and even necessary, to line the arch. Mica-schist, on the contrary, and particularly when loosened by distortion, most commonly requires to be substantially lined above the floor with masonry.

But many stones whose strength and texture would, if they remained unaltered by exposure, enable them to stand for ever, are affected by atmospheric air and moisture, and very speedily so by frost. Partially decomposed primitive rocks are subject to disintegration by such exposure. Decomposed granite, called by miners 'pot grawen,' is extremely troublesome in mining; it consists principally of felspar and potash, as does the china-clay, or kaolin, of the potteries. This substance appears to have been formed by the decomposing action of the air, or of chemically formed oxygen. Pyrites has a natural tendency to decomposition when exposed to the air, and it affects everything with which it comes into contact. Chalk is a material which, in those parts where it first crops out, that is, at the top of the stratum, has frequently given much trouble, by reason of its inequality and the common occurrence of pot-holes of loose gravel, which, when unduly charged with water, break away the surrounding chalk. The presence of chalk veins in the mica-schist formations of the St. Gothard Mountain have been found to expose the rock to decomposition when opened to the air by the excavations for the tunnel. The diluvial strata are from their nature the least compact, and therefore require the most careful treatment. The alteration, too, in their position, which, at some remote period of time, has uplifted and distorted the original horizontal strata, renders them liable to further change of form, by facilitating the operation of water—the element to which they owe their formation origi-

nally, and to whose continued action they seem peculiarly susceptible. Of these formations, the most solid are gravel and sand. The other soils of this class are extremely variable. Some clays are firm and tenacious; others, of a marly character, are slippery; while quicksands and peat are proverbially treacherous. Clays, too, may be intersected by porous veins; which act as conduits for water. The London clay has a notorious reputation with well-sinkers; even in the absence of moisture, if the clay be left exposed to the air for a few hours, it expands and bulges inwards. A well at Richmond, of four feet in diameter, was completely closed in one night by the swelling up of the bottom, although there was not any water in it. In mining operations, the expansion of clay is well understood. The floors of old mines are always expected to swell upwards. The action of the air upon shale is well known; shale, though so tough and hard underground as to require the agency of gunpowder for its excavation, swells when uncovered, and becomes, after a few weeks of exposure to damp and atmospheric action, thoroughly decomposed, and falls to powder. In the tunnel on the Manchester and Bolton Railway, the timbers used in its construction were frequently broken by the expansion of the clay, although it appeared quite dry. In the Primrose Hill and the Kilsby Tunnels of the London and Birmingham Railway, if the cutting was left for a few days without having the brick arching completed, the timbers were broken. In the former case, the expansion, arising from exposure to air, appeared to be nearly the same as in the latter case, from exposure to water. In the Box Tunnel, on the Great Western Railway, it was usual to allow six inches for expansion between the face of the work and the timbers, and even that amount of clearance was scarcely sufficient. Mr. Simms' experience with the Blechingley and Saltwood Tunnels was of the same character.

When chemical action begins, electrical currents may be started, and the flow of electricity through the veins and fissures of mineral substances might set up a decomposition, and with that a change of form. This action cannot be continued without a corresponding alteration of the bulk of the mass, which might be set in motion by a slight degree of expansion or contraction. Primary rocks are subject to such effects, and in sinking through porphyritic

rocks, fissures are frequently found, filled with foreign matter, which swells and forces in the sides of shafts, when such an event may be least expected.

In the agreements entered into with the contractor for the formation of a railway tunnel, the price of the work, and a schedule or scale of prices by which any extra or additional works are to be executed, is given by the contractor. In the specification, prepared by the engineer, the mode of payment and the nature of any retentions, if such there should be, is stated. The time for completion and the fines for exceeding this period are also specified, with the condition that all payments are subject to the engineer's approval of the work. The contractor finds tools, labour, and materials, gets out all foundations, excavations, shafts, culverts, drains, roads, &c., and provides centreings, pumping machinery, scaffolding, fencing, and other requisite materials of every description, according to the specification, plans, and instructions, which he may from time to time receive from the engineer. He lays the permanent way, the materials for which are found for him by the company. When he does not employ a sufficient number of men on the work, the engineer should have the power to engage more, after giving him a week's notice to that effect. These men may be retained temporarily or permanently as may be required, in all cases using the contractor's materials, the pay of the men being deducted from the price of his contract. The ground over the tunnel should be fenced off previously to the commencement of the work. The contractor should be restricted from entering on any adjoining land without leave, and if this should be necessary, after the leave is obtained, the land should be immediately fenced off. Temporary roads for the conveyance of materials from the high roads when required should be formed by the contractor, also those necessary for removing the spoil-earth.

The contractor should further be bound to alter or take down any work not approved by the engineer. All materials, from the moment that they are brought upon the site of the works, become the property of the company, and the contractor is not to remove them without permission; but the company is not answerable for damage which any material may sustain. These and similar clauses in the agreement are of course only provided in cases of special emergency, and are seldom required to be acted on. The con-

tractor is supplied with copies of plans and sections, and of the specifications the correctness of which he ascertains for himself; he is also to do all that may be reasonably implied, if not actually expressed in the drawings and the specification. It is usual to deduct 10 per cent. from the payments, and the deductions are not paid to the contractor till twelve months after the completion of the work, during which period he is bound to maintain the work in good condition. The payments are in general made monthly, including those for extra and additional works, after the work done has been approved by the engineer. It is also usual, in large works of this kind, when the contractor has more than two millions of bricks on the site of the work, to allow him half or two-thirds of their cost.

When the work of tunnelling is about to be commenced, the cuttings which approach the ends of the tunnel to be made are carried up to the points where the boring is to begin. The faces are then scraped, and the men are set to work at the tunnel at both ends. In the excavation of short tunnels they are formed from the ends only; but when they are of considerable length, vertical working shafts are sunk from the surface of the hill above to the required level, generally in the line of the longitudinal axis of the tunnel. The shafts are made sufficiently wide to admit of the lowering and raising of men and materials and excavated stuff, by means of windlasses, horse-gins, or steam-engines; and of fixing pumps.

When the shafts are finished, the work of excavating the headings and forming the tunnel is commenced at each shaft; and thus, in fact, several short tunnels are made, which are ultimately united or joined into one tunnel. In this way a great number of men may be employed on the undertaking at the same time, without confusion, and it is evident that the time within which the tunnel may be completed may be proportionally reduced.

There is a class of tunnels, such as pass through the side of a hill or a mountain, for the construction of which side drifts horizontally from the face of the hill are made, instead of vertical shafts; side drifts offer the same facilities as vertical shafts for opening any number of working faces for the excavation of the tunnel.

But there is another class of tunnels which involves an entirely different system of construction—tunnels of great length under mountains of great breadth and elevation—the Hoosac Tunnel, in America, and the Mont Cenis and St. Gothard Tunnels in Europe. For the construction of such tunnels neither shafts nor lateral drifts can feasibly be applied, and consequently the operations for excavating and building the tunnel are restricted to the two ends. Tunnels in such a situation are necessarily cut through rock formations; hence the aid of the most efficient apparatus for blasting operations is required—rock-drills or mechanical perforators, worked by compressed air supplied by compressors at the surface.

CHAPTER I.

GEOLOGICAL FEATURES OF THE SOUTH-EASTERN RAILWAY—GENERAL ACCOUNT OF BLECHINGLEY AND SALTWOOD TUNNELS.

The Blechingley and Saltwood Tunnels are situated upon the line of the South-Eastern Railway between London and Dover, which passes through a district of country not only celebrated for the beauty of its landscape, but highly interesting to the Geological enquirer—the Railway being formed through the Tertiary strata and the cretaceous group of the Secondary formation. Commencing at the Metropolis, it is constructed upon the London Clay till it reaches New Cross; where, at about one hundred yards to the south of the public road bridge, the Plastic Clay formation appears on the slopes near the bottom of the excavation, in situ beneath the London Clay. The junction of the two formations at this place is described in an interesting paper read before the Geological Society, April 17, 1844, by H. Warburton, Esq., the President, containing some results of an examination of that

locality, in which I had the pleasure of assisting him; and is represented in the following section.

London Clay:

1.	Yellow clay	thickness not determined.
	Blue or slate-coloured clay . . .	thickness 10 to 15 feet.

Plastic Clay formation:

			ft.	*in.*
2.	Rolled flint pebbles or shingle	thickness	1	10
3.	Fine fawn-coloured sand		0	3
4.	Lignite		0	0½
5.	Fine fawn-coloured sand		2	0
6.	Ferruginous sand, with marine fossils, oyster shells, and cerithia . .		0	4
7.	Loose grey sand, with fragments of cerithia		0	8
8.	Strong black clay		0	10
9.	Black clay and sand, with fragments of oysters and cerithia . .		0	9
10.	Black dirty sand		0	4
11.	Dark sand, containing fossils, oyster shells, &c.		0	6
12.	Calcareous stone, containing paludina, unio, &c. (freshwater fossils) .		0	6
13.	Decomposed stone and sand, with oysters, &c.		0	3

The shells belonging to the upper part of the Plastic Clay series in this neighbourhood have been well described by Dr. Buckland in the fourth volume of the first series of the Geological Society's Transactions, but the occurrence of the paludina and unio in the stratum No. 12 of the above section, which are freshwater shells, thus included between marine fossils, appears to have escaped observation, till now discovered by Mr. Warburton; who describes the stone in which they are embedded as septaria of a texture considerably more earthy than the septaria of the London Clay usually are.

The line of Railway continues upon the Plastic Clay as far as Combe Lane, Croydon, where the Chalk crops out from beneath the sands of the last-named formation, and is distinctly to be seen on the north-east slope of the cutting. The Railway then crosses the great Chalk range that extends from Dover to Hampshire, and rises towards the Chalk escarpment at Merstham, in Surrey, where its greatest summit level between London and Dover is attained in the tunnel near that place.

In the deep cutting at the south of the tunnel, a good section of the Upper Green Sand stratum appears, cropping out from beneath the Chalk;

this is succeeded at the village of Merstham by the Gault, through which the road to Blechingley has been lowered that it might be passed under the Railway.

At a short distance further southward, the Lower Green Sand formation rises to the surface, in beds of fawn-coloured sand, very siliceous, and good for engineering purposes. The middle beds of the Lower Green Sand, as indicated by the presence of rushes and wet land, next appear; and these are followed by the lower beds of the same formation, which contain the Kentish ragstone, fuller's earth, &c.—the fuller's earth pits of Nutfield being near this locality. The lower beds of this formation rise to a considerable height, and form the range of sand hills that passes through the country, parallel to the great chalk range before named.

The place where the railway crosses the sand range is called Redstone Hill, and is the point where the Brighton railway diverges to the south, while the Dover railway passes round the hill with a curve of half-a-mile radius to the eastward; and towards the further end of this curve, near to a bridge at Robert's Hole Farm, the next inferior stratum, the Weald Clay, emerges from beneath the sand. This spot may be further identified by the greater width of the excavation, or flatness of the slopes, occasioned by the slipping of the earth at the junction of the two formations, where much water was present. In making this excavation, some stone was found, that was much jointed, and contained innumerable fossils, which, upon examination in April 1843, by Mr. Warburton, Dr. Fitton, Mr. Austen, and myself, was found to include some of the most characteristic of M. Leymerie's Neocomien species, with a few belonging also to the quarrystone of Hythe; as, arca raulini, panopœa depressa, pholadomya acutisulcata (Leymerie), pecten obliquus (interstriatus), pinna sulcifera, gervillia aviculoides, perna mulleti, p. alæformis, trigonia dœdalea, t. Fittoni, gryphæa sinuata, nautilus radiatus, &c. This stone appears to correspond with the Atherfield rocks in the Isle of Wight; which it resembles in its mineralogical and geological character. [See paper by Dr. Fitton, read before the Geological Society, May 24, 1843, entitled 'Observations on the Section of the Lower Green Sand at Atherfield, on the coast of the Isle of Wight.']

From Redstone Hill the line passes eastward, along the Weald Clay, in successive cuttings and embankments for many miles, except that near Blechingley there is a tunnel, bearing that name, formed through a spur of Tilburstow Hill: the Weald Clay at this place is indurated into a shale, or blue bind, and being full of joints and faults, caused much difficulty in the work, as will be described in the following pages. The fossils found during the construction of the tunnel were portions of the iguanodon, hylœosaurus, cypris, paludina, clathraria (Lyelli), &c. &c., and a fine specimen of the lepidotus (Mantelli), presented by me to the Geological Society, accompanied by a short paper upon the subject of the strata at this place, which was read at the Society's meeting, on February 21, 1844.

Near the town of Ashford the line leaves the Weald Clay, and again enters upon the Lower Green Sand formation, which continues to be its base as far as Folkestone, a distance of about fifteen miles; the summit is passed by means of a tunnel, at Saltwood, not far from the out-crop of the Sand from beneath the Gault; consequently the shafts were sunk through the upper beds, and the tunnel is formed at the junction between that and the middle bed; where a large quantity of water was encountered, which greatly retarded the progress of the works. Among numerous fossil remains found at Saltwood, chiefly in ferruginous concretions, the following may be particularly enumerated: nautilus radiatus, gervillia aviculoides, terebratula, tethys major, panopœa, trigonia alœformis, venus, cardium, tornatella, pecten quinquecostatus, p. orbicularis, &c. &c., with fossil coniferous wood pierced by gastrochæna; together with a remarkable product, a new and beautiful resin, which partakes of the properties of amber and of retin-asphalt, and is principally marked by its clear red colour, its infusibility, and the difficulty with which it is acted upon by many chemical solvents. I was indebted to Mr. Edward Solly, through the kindness of Dr. Fitton, for a chemical examination of this substance, the results of which are inserted at length in a paper read before the Geological Society, June 7, 1843, giving an account of an investigation of the strata from the summit of the Chalk escarpment above Saltwood Tunnel to the sea at Hythe; or at right angles both to the

range of hills and the direction of the line of Railway in that locality. It may not be uninteresting to insert the result of such examination.

The Upper Green Sand stratum, which at the back of the Isle of Wight is one hundred and four feet thick, is here altogether wanting, it having thinned out at this place.

Strata from beneath the Chalk to the Wealden, through Saltwood.

	ft.	in.	ft.	in.	ft.	in.
Upper Green Sand, ... (wanting,—but) at Folkestone, five miles distant, it is in thickness					15	0
Gault					126	0
Lower Green Sand.						
Upper Division			70	0	406	6
Middle do.			158	0		
Sand above the quarries . .	67	0	178	6		
Quarry Rock	48	0				
Sand and Stone, previously concealed	14	0				
Clay beneath the sand and stone .	49	6				
Total thickness from the Chalk to the Wealden					547	6

Near Folkestone station the line leaves the Sand, and crosses the Gault formation; where, at the junction of that stratum with the Upper Green Sand, and then of the Chalk above, a tunnel is made through the hill to the undercliff called the Warren, and from thence to Dover, entirely in the Chalk, through and along the face of the cliffs—altogether one of the grandest engineering works in the kingdom—and where Mr. Cubitt, the Engineer-in-Chief to the Railway Company, so successfully introduced the use of gunpowder in blasting rock upon a great scale, especially in removing that large mass of chalk, 'The Round Down,' on January 26, 1843: the particulars of which are given by Lieutenant Hutchinson, R.E., in the sixth volume of the Professional Papers of the Corps of Royal Engineers.

Such are the Geological Features of this line of Railway.

The Engineer-in-Chief charged with the construction of the line was William Cubitt, Esq., F.R.S., &c. &c. That gentleman divided the whole line into three districts; over each of which he appointed a resident Engineer; to that nearest London he appointed the author; the district through the

Weald of Kent was assigned to Mr. Barlow; and the third, or Dover district, was given to Mr. Wright. In the district first named the Blechingley Tunnel is situated: and, upon its completion, the author was further appointed to superintend the construction of the tunnel at Saltwood—the particulars of which two works form the subject of the following pages. And to my colleagues and myself it is gratifying to know that our Engineer-in-Chief has expressed himself, both in public and private, satisfied with the manner in which we, severally, have carried his views and intentions into execution.

A general description of the Blechingley and Saltwood Tunnels, explaining the circumstances under which they were constructed, is annexed, previously to entering upon the details of the same.

The form and the several dimensions of these tunnels, as they were constructed, are shown at fig. 3, Plate I. The figure is divided into two parts by a vertical line: the left-hand half shows a transverse section of Blechingley Tunnel; and the right-hand half shows a similar section of Saltwood Tunnel: the only difference in the two sections being that the inverted arch of Slatwood Tunnel had a rise, or verse sine, of three feet six inches; whereas that of Blechingley was but three feet. This difference was thought necessary, to insure sufficient stability in the former.

The figure of each tunnel, from the springing of the invert on the one side, over head, to the same point on the opposite side, was elliptical, and described with arcs of circles whose radii was 21 feet, 15 feet, and 9 feet. The small circles, and the dotted lines, show the various centres and the extent of the said arcs. The invert of Blechingley Tunnel, with a rise of three feet, was struck with a radius of 22 feet 1½ inch; and that of Saltwood Tunnel, with a rise of three feet six inches, was struck with a radius of 19 feet 5¾ inches.

The thickness of the brickwork of the invert of the shaft and side lengths in both tunnels, and for the first leading length at Saltwood Tunnel was 2 feet 3 inches; and for the remainder, 18 inches was considered ample. The side walls and arch at Blechingley Tunnel were 3 feet thick for the shaft and side lengths; this was, however, reduced to 1 foot 10½ inches wherever the

ground was sufficiently sound and undisturbed to admit of it being safely done. At Saltwood Tunnel, the shaft, side, and first leading lengths were 3 feet, or four bricks thick; and the remainder of the work 2 feet 3 inches, or three bricks thick. The whole work of both tunnels was set in cement.

The clear height from the upper surface of the rails to the crown of the arch was 21 feet, and the clear width at 5 feet above the said level was 24 feet. The skewbacks and footings were also of brick; and at Blechingley wedge-formed bricks were made for this purpose, as shown in section at fig. 2, Plate V.

BLECHINGLEY TUNNEL.

So named from the parish where it is situated, is in the county of Surrey, and about twenty-five miles from London. The tunnel is twenty-four feet wide in the clear, and twenty-one feet from the upper surface of the rails to the crown of the arch; its figure is elliptical above the skewback or springing of the invert; the versed sine of the invert is three feet, and the level of the rails is one foot above the skewback. The tunnel is inclined from west to east, at the rate of three feet per mile. The dimensions of the brickwork varied, and were regulated according to the appearances of the ground, from time to time, as the lengths, which were twelve feet long, were excavated: these particulars are given in figure 3, Plate I., the left half of which shows half the cross section of the tunnel at Blechingley; and the right half that at Saltwood. Figure 1, Plate I., is a longitudinal section of Blechingley Tunnel, and figure 2 that at Saltwood; showing the positions of the working shafts, and of the observatory, &c.—all of which subjects will be described in further details in the course of the work in each tunnel.

The ridge through which the tunnel passes is the main axis of elevation of this part of the country; and, from the dip of the strata in both directions from its summit, forms a north and south anticlinal axis, its direction being that of the meridian, nearly; which, so far as I can judge, extends from the chalk ranges between Godstone and Merstham in Surrey, to about Ditchling in Sussex; the waters which fall on the surface along the said line of direction form sources or feeders to the rivers Medway and Ouse on the

east, and to the Mole and Adur on the west. Besides the inclination of the bed both ways from the axis they dip to the north at an angle of about thirteen degrees; but westward, from the summit of the ridge, there is no regularity in this respect, the strata lying as it were in heaps, at almost every angle, from five to sixty degrees, and dipping in all directions, from west-by-north to east; besides which a detached mass of sand-rock lay across my path, near the top of the tunnel, and from whence a great body of water was discharged into the workings, causing no small trouble and difficulty.

The Blue Clay of the Weald in which I was working was at first greasy to the touch; and when dry and in situ, formed a hard shale, requiring an extensive use of gunpowder in its excavation, but upon exposure to damp and atmospheric action, it swelled considerably and then slaked: this obliged me to close-pole the face of the work in all directions as far down as the lower sill, and frequently to the bottom. The expansion or swelling was occasionally so great as to threaten the hurling in of the lengths after they were completely timbered, and would probably have done so but for constant watchfulness, and strong timbers properly applied. The pressure upon the work was sometimes so great that sound oak bars, fourteen or fifteen inches in diameter, were cracked and broken as if they had been mere sticks.

The pressure we had to contend with was variable and uncertain in the highest degree; sometimes a length could be got out, and the arch turned without any apparent movement of the earth around and above us; at other times, the ground when partly excavated would begin to move, and press upon the bars on one side of the arch; at others, it would act upon the crown bars; the former action was principally confined to those parts of the tunnel that were deepest below the surface, whilst the greatest pressure (which mostly acted upon the crown) took place towards the ends of the tunnel, where the surface was so much nearer to the arch. It sometimes occurred that after a length had been excavated satisfactorily, and by the time that the bricklayers had built up the side walls, the weight on the top was so great as to press the bars down to an extent nearly equal to their own thickness, which was seldom less than fifteen inches; consequently, when the centres were set, there was not sufficient

space between them and the bars to insert the brickwork of the arch; the remedy for this was to remove the poling, and excavate more earth from above the bars, and to prop them again at a higher level; which occasioned considerable loss of time, and consequently increased the expense.

In one of the pits—No 11, at the east end—this weighting of the crown occurred constantly after getting in three lengths west of the shaft, and therefore we elevated the extremity of the bars sufficiently high, upon their first insertion, to allow for the expected subsidence: in the other pits its occurrence was uncertain; consequently it was impossible to provide for it, without running the risk of having a great opening above the arch, to be filled solid with brickwork, or with earth, which is often imperfectly done, and would be liable to bring a greater weight upon the work when the earth again takes its bearing, after the mass has been in motion. It is the general movement of the mass in adjusting itself to equilibrium, after the disturbance occasioned by the excavation, that causes the weight, and whose searching influence finds out the weak points in the work.

The greater pressure upon the work in shallow ground over that where the tunnel is very deep below the surface, I can explain only upon the supposition that in the former case, the whole superincumbent mass is acting perpendicularly downwards; whilst, in the latter case, a small portion only gets into motion, the upper part acting as a key (if I may so express myself), by which the mass supports itself. This action was clearly shown in pit No. 11, above referred to; where the working below could be distinctly traced upon the surface of the ground, by its sinking in the form of a basin as our work proceeded, and at the same time cracking into large fissures.

The sinking of the shafts was commenced in the beginning of August 1840. These were down to the depth necessary for the shaft-sills by the middle of September; which, together with the further sinking, including the square timbering to the bottom of the tunnel, was completed by the end of October. The driving of the heading at the level of the top of the invert was then commenced, and was finished by Christmas. From this time till February 12, 1841, preparations were made for commencing the excavation of the tunnel: these consisted in making a gin for each shaft, and the ground-

moulds, leading-frames, and centres. On the above date the miners broke ground in No. 3 pit, being the first commencement of the tunnelling; but it was not until early in April that the whole of the shafts were got to work: and as soon as each was started, the work was pushed on with the utmost vigour, night and day.

On September 3 the first junction was effected; and on November 1 the last junction was keyed in; the tunnel, as originally intended, was therefore complete; but it was resolved to extend it at each end in consequence of the backwardness of the open cuttings that were let to two different contractors. My instructions were to extend the tunnel until I should meet the open cutting, and thus enable the Directors to open the Railway to the public at the time proposed, which otherwise could not have been done. The extension of the tunnel, and the erection of the entrances, were not completed until early in the following May; and the Railway was opened to the public on May 26. The tunnel, as completed, is 1,324 yards in length.

Although it would appear, from what has above been stated, that the sinking of the shafts did not commence until the month of August, yet this must be understood as in reference to the working-shafts only; because, in the preceding February, two trial-shafts were sunk, to ascertain the character of the ground in which the tunnel was ultimately to be constructed. The particulars of this work will be given in Chapter IV. After two trial-shafts had been sunk, it still appeared desirable to examine the ground at two intermediate points; accordingly two other shafts were commenced early in the spring, and, to save expense, they were made the full size of working-shafts in the first instance, with the intention of employing them as such in the course of the work. The working-shafts were 9 feet in diameter, in the clear, while the trial-shafts were but 6 feet. These large shafts had, however, not been far proceeded with, when an unpleasant difference arose between the Company and the occupiers of the land, who demanded an exorbitant amount of compensation, forbidding the proceedings until such was paid. Under these circumstances the work was suspended until the following August; when the said differences having been adjusted, possession of the land was obtained, and the works were prosecuted with vigour.

Previously to laying the permanent way, a culvert was constructed upon the invert, throughout the tunnel, as shown in section, figure 3, plate I. The tunnel was also lime-whited twice, with a view of increasing the light; but this did not answer as was expected.

The monthly rate of progress, during the time the work was in full activity, was as follows. During May 1841, 104 yards were completed; June, 185 yards; July, 264 yards; and August, 228 yards. The bricks were all made on the ground, and wheeled or carted to the various shafts.

The construction of the tunnel was entrusted, by Mr. Cubitt, wholly to the author, who at the same time had charge of the works let to contractors, extending over nearly fourteen miles of the Railway. Upon its completion he proceeded with the plant to Saltwood to construct a similar tunnel there. In the execution of the preliminary works at Saltwood, difficulties of no ordinary character occurred; but by overcoming them the work was subsequently made comparatively easy, as will hereafter be described. The Board of Directors afterwards determined upon letting the construction of the tunnel (itself) to contractors; leaving the author to superintend the same, and look after the interests of the Company.

SALTWOOD TUNNEL.

This tunnel is also named after the parish wherein it is situate; and is 954 yards in length. Its form and dimensions are precisely the same as of that at Blechingley, except that the versed sine of the invert was made three feet six inches, instead of three feet. The thickness of the brickwork did not vary so much, neither was its average thickness so great; which arose from the more homogeneous character of the ground, after it had been drained by the preliminary works. The tunnel is inclined towards Dover, at the rate of twenty feet per mile, or 1 in 264. An examination of figs. 2 and 3, plate I., will show all that is requisite of these particulars. The former is a longitudinal section; and the right-hand half of the latter is a cross section of half the tunnel.

The tunnel is constructed at the top of the middle beds of the Lower

Green Sand; and is about ninety feet below the surface of the ground. This stratum contained, as it usually does, a great body of water, which occasioned the difficulty in sinking the shafts, and driving the heading, that will hereafter be described.

The sinking of the working-shafts, which were nine feet clear diameter, was commenced on June 11, 1842, and was carried on in the usual manner. The earth was raised to the surface by means of the common windlass, or jack-roll, at which four men could work; and had circumstances continued favourable, it was intended that no other machinery should have been used for that purpose, until the sinking and heading were completed; as had been previously done at Blechingley. An oak or elm curb was inserted at the bottom of each excavated length, on which the brickwork was carried up to underpin the preceding curb. The sections of the shaft, Plate II. show the windlass, &c. and the curbs inserted in their places; and give a correct notion of the whole. The bottom curb was so placed that the brickwork of the shaft should terminate eight feet above the level of the intended soffit of the arch.

The difficulties commenced about July 13; when the ground became a perfect quicksand. The sinking of the shafts, and driving of the heading, henceforth became difficult, tedious, and expensive, compared with what had been expected. Manual labour was insufficient to draw the water to the surface, and the horse-gins that had been brought from Blechingley were erected, and barrels holding one hundred gallons were substituted for the twenty-gallon buckets worked by the men. The average quantity of water drawn from each shaft, during the remainder of July, was 700 gallons per hour, when it increased to 1,600 gallons per hour, which brought with it large portions of sand from the back of the timbering, and added to both the difficulty and danger of the work; to secure the sand from running, the back of the polings was, at the time of their insertion, well packed with straw, which let the water pass, but retained the sand: this kind of packing was subsequently used throughout the work, and in all cases, when properly done, it answered the purpose.

By the end of August the average quantity of water drawn from each of the pits amounted to 23 barrels of 100 gallons each per hour; whilst at the

same time no more than one-half of a cubic yard of sand was raised to the surface. On the 31st of that month, the quantity of water drawn from No. 7 pit averaged 37½ barrels per hour, which, together with the small quantity of earth raised, gave, as the work of each horse for three hours, 42,637 lbs. raised one foot high in a minute.

The miners complained much of their employment, and were obliged to have three, and in some cases four shifts in every twenty-four hours; they were wet to the skin in a few minutes after they entered upon their work, and, in many instances, illness succeeded their constant working in the water. In addition to the quantity of water, we were troubled with foul air in shafts Nos. 10 and 13, which prevented the candles burning. (The latter was a supplementary shaft, to facilitate the bringing up the heading along the intended open cutting, and therefore is not shown in the longitudinal section in plate I.) The headings thus circumstanced were ventilated by an air-machine or what the workmen commonly call a 'Blow-George,' fixed at the top of the shafts; which is simply a fan-wheel revolving rapidly in a spiral-formed box, driving fresh air into the workings below, through tubes fixed in the shafts and along the headings, where the men were at work.

About the end of September the person who supplied the horses wished to withdraw them from the works, as so many had been knocked up, and several had died. Accordingly, endeavours were made to obtain others; and notices were issued around the country, advertising for horses; but the assistance thus obtained was very trifling, as the numerous carters then in the neighbourhood declined putting their cattle to the labour. The same party was therefore prevailed upon to continue his help.

The following statement will show about the amount of labour exacted from each horse, at the end of August, at the shafts then at work.

Number of Pounds raised one foot high per minute, by each Horse.	Number of Hours each Horse worked.
24,475	6
22,626	6
24,535	6
42,637	3
22,584	6
30,820	3

More minute particulars of the difficulties arising from the influx of water, and of the mode of proceeding whereby they were overcome, will be inserted in Chapters VI. and VII.; wherein the square timbering and heading driving are described, as being a more appropriate place for their insertion.

These exertions were necessary, because it was desirable that the preliminary works should be got through without having recourse to steam power for pumping; as that would at once have involved the Company in a great expense; especially as it appeared probable that if a heading, or adit, could be made quite through the hill, at the level of the bottom of the tunnel, with an outlet at the east end, leading to the natural drainage of the country, the whole of the water would run off from the works as it collected, and leave them sufficiently dry to admit of the work being proceeded with; which was as much as, at that time, it appeared reasonable to expect, the proposed inclination of the tunnel in that direction being ample for the purpose. This, by perseverance, was accomplished; but it was not until the end of October that the heading was completed, and the drainage effected.

The heading, when completed, was altogether 1,250 yards in length; as it not only extended throughout the length of the tunnel, but also under the open cutting at the east end, before an outlet could be obtained for the water; which there runs off into the valley of Newington, and joins the natural drainage of a large district of country that empties itself into the sea, at Hythe.

When the heading was effectually opened, it was considered desirable to ascertain the quantity of water that was continually passing away from it. Accordingly, a gauge was fixed at its outlet, which narrowed the opening to twelve inches in width, and the depth of water flowing over the waste-board (or between the sides of the twelve-inch opening) was noted from time to time. At first the depth was five inches, which indicated a discharge of about 359 gallons per minute, or 21,540 gallons per hour; but this quantity afterwards diminished, and for a length of time it averaged four inches in depth, which gave about 257 gallons per minute, or 15,420 gallons per hour. The first of these quantities being noted as soon as the heading was completed, confirmed the accuracy of the registered quan-

tity of water drawn to the surface by horse power, as will be explained in Chapter VII.

The following table shows, approximately, the quantity of water, in gallons, and in cubit feet, per minute, that passes over a waste-board twelve inches wide.

Depth on the waste-board in inches.	Water, per minute.	
	In Imperial Gallons.	In Cubic Feet.
1	32·1	5·14
2	90·8	14·53
3	167·0	26·71
4	257·0	41·12
5	359·2	57·47
6	472·1	75·54
7	595·0	95·20
8	726·9	116·30
9	867·3	138·77
10	1015·1	162·42

For any other width of gauge, a proportionate quantity of water will be discharged.

On November 1 the Board of Directors contracted with Messrs. Grissell and Peto, and Betts and Son, to construct the tunnel for the sum of £85,000, exclusive of the entrances, they allowing the Company £3,006 for the plant and materials, as they then stood upon the ground. The whole to be completed on or before June 1, 1843, or the contractors to forfeit the sum of £50 per day, from that date.

The work was executed under the author's superintendence, as Resident Engineer, and completed by the time named. The preliminary works that cost so much labour and anxiety during their construction fully answered the purposes for which they were designed, and drained the ground more effectually than was anticipated; this necessarily facilitated the progress of the work, and was highly advantageous to the Contractors.

The quantity of bricks used in the construction of Blechingley and Saltwood Tunnels, including the entrances, culverts, shaft towers, and all contingent works, was as follows:—

Blechingley . . .	14,696,005	or	11,099	per lineal yard.
Saltwood . . .	10,186,246	or	10,677	per lineal yard.

CHAPTER II.

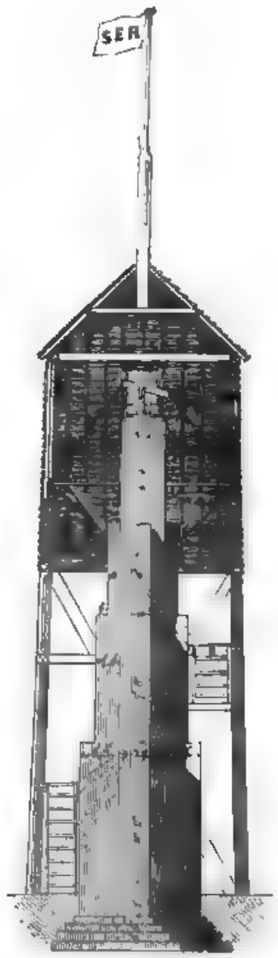
DESCRIPTION OF THE OBSERVATORY—THE TRANSIT INSTRUMENT AND METHOD OF FIXING AND ADJUSTING.

TUNNELS have generally been made straight from end to end; and I believe that the few exceptions (or curved tunnels) are of comparatively short lengths, and constructed through good ground, that would admit of a large excavation, or cavern, to be made throughout their whole extent, or nearly so, without requiring much timber to support the strata; consequently there could be but little difficulty in forming such a tunnel to the curve required; but in heavy ground they are made straight, not merely on account of the greater difficulty of construction otherwise (except in peculiar situations), but, for Railway purposes, it would be considered unsafe for the trains to be passing and repassing each other in darkness and a confined space, without the advantage of each engine-fire being visible from the other train for some distance.

The Blechingley and Saltwood Tunnels are both straight, and the centre line was carefully ranged with a transit instrument of thirty inches' focal length, having an object-glass of two and three quarters inches' aperture, mounted on a cast-iron stand. In order to command a view of every shaft on the work, the instrument was set up on the most elevated spot of ground, as near the middle of the tunnel as possible; and, that the view might be uninterrupted by the machinery and timber about the shafts, as well as the earth when brought up from below as the work proceeded, the transit was elevated considerably above the surface, by the erection of an observatory; and as such a building is only required during the construction of the tunnel, it is generally but a temporary erection; although there are instances of observatories for such works having been built of an expensive

character. The observatories at Blechingley and Saltwood were nearly similar to each other; and the following engraving, showing that at Saltwood, will give the reader a knowledge of the kind of building that will be sufficient for all such purposes, and, being composed of brick and timber, it may be taken down at an advanced period of the work, and the materials used up.

THE OBSERVATORY.

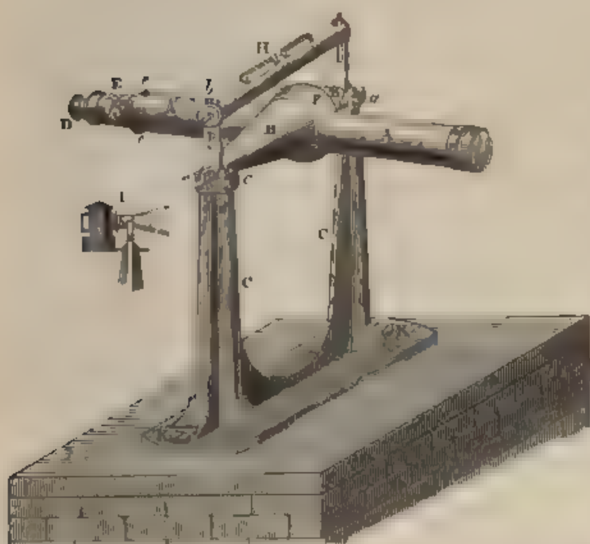


The annexed engraving shows a section of the Saltwood Observatory, taken in the direction of the tunnel, with the brick pier in the centre, surmounted with the Transit Instrument. The pier, which was 30 feet high, was erected over the centre-line of the intended tunnel, and quite independent of the rest of the building; so that any motion given to the building by high winds, or otherwise, might not be communicated to the pier. The object to be attained was great steadiness to the transit, which could not be ensured so well as by an erection of brickwork. The dimensions of the pier, and its counterforts, are given in the engraving. A flat stone was set on the top of the pier, to which the iron stand of the transit was screwed down, as shown in detail in the engraving of the instrument itself, which will be given in the next page.

The building requires but little description: it was composed of larch poles, intended for and afterwards used in the works, stiffened with struts and cross-pieces; the upper part, or observatory-room, was enclosed with quartering and feather-edged boards. The ascent was by steps from below through a trap-door in the floor; and the floor was trimmed so as not to touch the brick pier by about 5 or 6 inches. Narrow openings were made in the sides of the room, in the direction of the tunnel,

through which the observer might look each way for the ranging of the lines; these were closed with small sliding shutters, so that one or more of them could be opened at a time, leaving either a large or small aperture, as occasion might require. The whole was surmounted by a telegraph, having two arms, for the observer to signal for the ranging lines to be moved either to the right or to the left; and when the line was found to be correct, both arms were extended, thus denoting that the line was to be moved both to the *right* and to the *left* at the *same time*—a thing impossible; it was therefore to be fixed in its then position. In the engraving (facing the title-page), representing the works above ground at Blechingley, the telegraph is shown as signalling to the men setting the lines on the ranging-frame of the shaft at the right-hand of the picture.

THE TRANSIT INSTRUMENT.



The annexed engraving represents the Transit Instrument; which consists of a telescope, having an axis at right angles to its length, supported on a cast-iron stand. This is a standard instrument in every astronomical observatory; where it is adjusted to describe or define a vertical circle passing from the north to the south point of the horizon, through the zenith of the place, and is the best means of observing the passage of the celestial bodies across the plane of the meridian from which *time* is correctly derived: hence its name, 'Transit Instrument;' and, thus employed, it may not inappropriately be called the *hand* which points to the time as shown by that unerring dial, the starry heavens. The same construction which renders it

the instrument best adapted to trace a vertical plane for astronomical purposes makes it equally so to set out a right-line on the surface of the earth; or, our problem more properly is—*to find any number of points in a straight line connecting two given distant points, the instrument to be situated also between the given distant points.* The line thus connecting the distant points is the base of a vertical plane of small extent. To do this, the telescope, A A′, is made to revolve vertically upon a horizontal axis, B B, the pivots of which are supported by the upright arms, C C, of the iron stand.

It does not appear to be necessary in this place to explain how a vertical circle is described by such an instrument, but that its performance may be correct it is essential that the optical axis of the telescope, or line of collimation as it is called, should be precisely at right angles to the horizontal axis about which it resolves; and also that the extremities or pivots of the said horizontal axis where they rest in their bearings on the iron stand be precisely level with each other.

The telescope resembles those of theodolites and spirit levels, and for terrestrial purposes is supplied with a similarly-arranged system of cross wires, the intersection of the centre wires with each other represents, when in proper adjustment, the line of collimation, or optical axis of the telescope. The slide D, or eye-piece, is movable in or out, to obtain distinct vision of the cross wires: an adjustment that must be made or verified each time that the instrument is set up for use, and so long as its eye-piece remains undisturbed it will require no repetition for the same eye; but would, in all probability, require alteration to suit the eye of another person. In adjusting the eye-piece to obtain distinct vision of the wires, it will be found that it can be accomplished with greater certainty by directing the telescope to a white sheet of paper, held or fastened at a little distance off, or even pointed to the sky, so that the wires may appear to be projected on a clear disc.

The screw E gives motion to a rack and pinion, which is the means of diminishing or increasing the distance between the object and eye-glasses, or rather, I should say, between the object-glass and the cross wires, and thereby produces distinct vision of the distant object to be observed. It should be ascertained that both of the above adjustments be quite perfect, before any

determinate observation is made, otherwise a parallax will exist, which will prevent an accurate result being obtained: what is called parallax, in this case, is an apparent motion between the object viewed and the wires of the telescope, and is detected when the observer moves his eye up and down, or sideways, while looking through the telescope. The adjustment of the eye-piece to the wires, and of the wires to the focus of the object-glass, so as to avoid parallax, requires a nicety which practice alone will impart to the observer; and which must always be repeated till it is accomplished.

That the weight of the telescope may not cause the horizontal axis to bend, the latter is made of two cones, B B, whose bases are connected together (to form the axis) and to the telescope by the intervention of a sphere, F, through which the telescope appears to pass; it in reality however forms the nucleus of the instrument, to which the tubes A and A′ forming the telescope, as well as the two cones forming the axis B B, are attached. The apex of each cone is finished with a steel or bell-metal cylindrical pivot, turned and ground upon the axis as true as possible. Much of the excellence of the instrument depends upon this being correctly and well done, for if they are not true, the telescope cannot possibly describe a vertical plane. These pivots work in v-formed sockets, or Y's, as they are technically called, which surmount the upright arms C C, of the iron stand.

To test the horizontality of the axis, a spirit-level, H, is placed striding across the instrument with its standards resting upon the pivots; for it is clear that if the pivots of the axis are horizontal (all other things being correct) the telescope, when elevated or depressed, or turned completely over and pointed in the opposite direction, must continue in the same vertical plane; when we thus say 'the telescope,' it must be understood to mean the line of collimation, or central intersection of the cross wires of a properly adjusted instrument. One or two thin brass plates are generally supplied in the box with the instrument, which may be attached, by a milled-headed screw, to the top of the arms of the stand. These are notched at their tops to receive a pin fixed in the end of the tube of the level H, which thus prevents the possibility of the level falling off the instrument when in use.

The cross wires in the telescope generally consist of a single thread of a

spider's web, which, at the same time that they are extremely fine, are perfectly opaque, and are not found to be fringed with light along their edges, as is sometimes the case when other fine material is employed. The volume of light which passes through the telescope in the day-time shows up these cross wires, but in using the instrument at night to range a distant lamp, or if need be, underground, the wires would not be visible, and, therefore, the instrument would be useless under such circumstances; to obviate this, and also to enable the possessor of such an instrument to amuse himself at his leisure (if he does nothing more useful), with observing transits of the heavenly bodies, one of the pivots is perforated through the cone B, and sphere F, and the light from a lamp or lantern adapted to the top of the stand passes through the said perforation, and falling on a diagonal reflector, situated in the sphere, is thence thrown upon the focus of the instrument, where the wires are fixed, near to the eye-piece. The reflector is also perforated to allow of the passage of the cone of rays in their convergence from the object-glass to the said focus, and thus distinct vision, both of the distant object to be viewed and of the cross wires is obtained by night as well as by day. The detached figure I shows the lantern in its position when used as above described.

The iron stand is fastened to the stone after it is placed in the required position, by means of the screws K K, which work into sockets previously let into the stone; the holes in the stand through which the screws pass are *drawn*, to allow of a small motion being given to the stand to perfect its adjustment in position, before the screws are made tight.

THE ADJUSTMENTS AND FIXING OF THE TRANSIT INSTRUMENT.—Long before it is necessary to commence working operations, the direction of the intended tunnel must be known nearly, and should have been staked out.

The most suitable spot must be selected for the observatory, so as to command a view of the whole length of the work, and its erection forthwith proceeded with; also, if possible, a permanent mark should be set up at a distance from each end of the tunnel precisely in the intended line, for future reference and the occasional adjustment of the transit; these marks should be placed where there would be but little chance of their being disturbed or

removed. For this purpose at Blechingley Tunnel I caused to be erected two brick piers, about five feet high, at the distance of full two miles from each end of the tunnel. There is an advantage in having them at a great distance, as far as accuracy is concerned in the adjustment of the transit, but in thick weather they cannot be seen, and therefore other similar marks should also be set up at shorter distances. All these piers were painted black, with a white line, from two to six inches wide (according to their distances) to denote the precise line with which the centre of the tunnel was to be coincident throughout its whole length. A straight line from the centre of one of the above-described distant marks, to the centre of the other (in the opposite direction), must pass through the telescope of the transit instrument when set for use, so as to coincide with the line of collimation. How to fix the telescope in a position to answer these conditions will be presently described.

To examine and adjust the line of collimation.—When the instrument is placed on its stand, direct the telescope to some small, distant, well-defined object (the more distant the better), and bisect it with the central intersection of the cross wires; then lift the telescope very carefully out of its angular bearings, or Y's, and replace it with the axis reversed; point the telescope again to the same object, and if it be still bisected, the collimation adjustment is correct; if not, move the wires one half of the error, by turning the small screws which hold the diaphragm with the cross wires near the eye-end of the telescope, and the adjustment will be accomplished; but, as half the deviation may not have been correctly estimated in moving the wires, it becomes necessary to verify the adjustment by moving the telescope the other half, which is done by turning the screws C C, near the top of one of the arms of the iron stand. Having thus again bisected the object, reverse the axis as before, and if half the error has been correctly estimated the object will be bisected upon the telescope being directed to it; if not quite correct, the operation of reversing and correcting half the error, in the same manner, must be gone through again until by successive approximations, the object is found to be bisected in both positions of the axis. The adjustment will then be perfect.

To set the Axis of the Telescope truly Horizontal.—Set the level H upon the pivots of the axis (as shown in the engraving), and by turning a milled-headed screw, *a*, near the top of one of the arms of the stand, raise or depress that Y, and with it the pivot that rests on it, till the spirit-bubble stands central in its tube; now reverse the level, that is, turn it end for end, and if the bubble again becomes central, it is clear that the axis is horizontal; but if it should not become central when reversed, it is equally clear that the axis is not only *not* horizontal, but that the level is out of adjustment also. To effect this twofold adjustment, half the error must be corrected by raising or depressing the screw *a* on the stand, and the other half by turning the capstan screws *b b*, at one end of the level, which raises or depresses the spirit-bubble with respect to its points of support that rest on the telescope pivots. It will, however, be obvious that the axis of the instrument will have been correctly levelled by the first part of the process, namely, *raising or depressing the screw a*, even though the error of the level be left untouched; but it will be found convenient to correct the latter error at the same time, as above described. These corrections, like those for the adjustment of the line of collimation, frequently require to be made several times before the adjustments are satisfactory; and when perfect, the spirit-bubble will remain central in the glass tube, both before and after its reversion. A graduated ivory scale is fixed along the top of the level, by which the amount of deviation from horizontality can be more correctly determined, and which scale for astronomical purposes is made to denote the angular deviation of the axis at the moment of observation. The value, in arc, of each division having been previously determined, a correction due to such error may subsequently be computed, and applied to reduce the observation to what it would have been had the axis been truly horizontal: but such minutiæ do not enter into the business of a Mining Engineer.

To fix the Transit-stand on the stone pier, and set the Instrument for use.—The instrument being set on the stone, move it, stand and all, until the telescope very nearly coincides with the two distant marks when directed alternately to them. Having thus approximately placed it, set up the level

H, and adjust for horizontality (the collimation adjustment having previously been verified); now move the instrument very quietly till the telescope coincides with one of the distant marks, keeping the axis horizontal throughout this part of the business; then turn the telescope over, and look in the other direction—(the observer must always remember to remove the level before he turns the telescope over, or he will most probably injure, if not destroy it); see if the coincidence with the other mark is correct; if it is not, observe the amount of deviation, and as nearly as can be judged move the stand laterally (or sideways) to correct one half of the deviation, and, by gently pushing one end of the stand from you, correct the other half. If these movements have been made judiciously, the telescope will be found, upon reversion, to cut both the distant marks; or otherwise they must be repeated till it is accomplished *very nearly*, so as easily to be perfected before the stand is finally screwed down, which must next be done.

The position of the instrument having thus been approximately settled, mark on the stone the position of the screw-holes in the bottom of the stand, and a mason can let into the stone the screw-sockets, which may be fastened with melted lead, plaster, or cement. This done, again set the instrument up, and insert the screws K K into the sockets, through the holes in the iron stand; which again approximately places the instrument in position. This approximation being now made very close, by repeating the foregoing operation, the final touch may be put to it, by first carefully examining and correcting its horizontality; making the cross wires intersect one of the distant marks most carefully, by turning the capstan-headed pushing-screws *c c*, on the top of the other arm of the stand. This gives a horizontal motion to the Y, and hence to the pivot which it carries: now reverse the telescope, by turning it over on its axis, and see if the other distant mark is also bisected; if so, all is well; if not, correct half the error by the capstan screws *c c*, and gently *tap* or *slide* the stand laterally the other half; the holes for the screws K K being drawn or made sufficiently large to admit of this small motion being given to the stand. This adjustment, like all the others, sometimes requires repeating, especially if not done with delicacy and care. When done, the screws K K may be made fast.

The method now described of bringing the instrument exactly into line may appear rude and difficult to accomplish, as it requires a nicety of touch which experience in the use of mathematical instruments (almost) alone imparts to the observer. To overcome this objection, by imparting mechanically a lateral motion to the stand, some of them are constructed with a double frame: in which case, the lower one is first firmly fixed to the stone (approximately in position), and the upper one is then rectified by means of screw adjustments, not unlike one of the motions of a *slide rest*—which is a great convenience, but adds considerably to the cost.

When the stone is being fixed on the top of the brick pier, it should be set correctly level on the upper surface; otherwise much trouble will result in subsequently fixing the instrument.

The foregoing are the adjustments necessary upon the setting up of the transit instrument; and, although it be ever so correctly done, it will require to be verified each time the instrument is used for ranging the lines, to ascertain that no derangement has taken place. To prevent this as much as possible, except from causes over which the observer has no control, he should lock up his observatory when he leaves it, and keep the key in his own possession, to prevent the ingress of ignorant and curious persons, who are too frequently prompted, although unintentionally, to do mischief.

A transit instrument is of all others the best adapted for ranging straight lines: and for such purposes, where great accuracy has been required, they have been used for a long time past: as in the setting out of the base line upon which the great trigonometrical surveys have been founded, both in this country and in distant parts of the globe. Likewise in surveys of small districts. Even in the preparation of parish plans, after the manner directed by the Tithe Commissioners, an instrument of this kind is highly useful for ranging accurately the long lines intended for measurement, for it is not sufficient that the measurements be correct, if the lines have not been set out perfectly straight.

In setting out about fourteen miles of the South-Eastern Railway, from Redhill in Surrey to Chiddingstone in Kent, through both a hilly and thickly-wooded country, the author found the use of the transit invaluable

for the purpose. The Railway through this portion consists of a few long straight lines which lie nearly in the same straight line; and, having found a few given points on elevated spots, he was enabled, by the superior power of the transit instrument, to range each straight line both ways for long distances, with the greatest precision. The instrument used on that occasion was of small magnitude compared with the one described in the preceding pages: it was portable, and adapted to a stout tripod stand, which ensured its steadiness; and when removed from the stand it could be placed in a conveniently formed box, and carried from spot to spot wherever its use was required. The top of the stand had also a lateralmotion, to enable the centre of the instrument to be brought readily over any precise spot on the line. Theodolites are now sometimes made with a transit telescope; which gives to those valuable instruments a great additional advantage.

The possessor of a transit instrument may likewise employ it for astronomical purposes, by placing it on a small brick pier in a garden or yard, and temporarily covering it over, to preserve it from the weather. For details of its practical application to such purposes, the reader is referred to a 'Treatise on Mathematical Instruments employed in Surveying, Levelling, and Astronomy,' by J. F. Heather, M.A., late of the Royal Military Academy, Woolwich, in WEALE'S RUDIMENTARY SERIES.

CHAPTER III.

SETTING OUT THE SHAFTS—RANGING THE LINE BOTH ABOVE AND UNDER GROUND—TAKING THE LEVELS, AND ESTABLISHING BENCH-MARKS, OR POINTS OF REFERENCE—ETC.

When the transit instrument is in perfect order, as described in the last chapter, the centre of each shaft may be ranged, and staked out, so that they may be all in a perfectly straight line. The number of shafts, and hence their distances apart, will depend upon the speed with which the work is required to be executed. In ordinary kinds of strata, if the work is required to be completed in twelve months, the interval between the shafts should not exceed one hundred yards; but I believe that about two hundred yards has been the distance more generally adopted. It will be found convenient to have the shafts equidistant from each other, unless some peculiar form or circumstances of the surface call for a different arrangement.

As soon as the shafts are sunk to their proper depth (the mode of doing which is described in the following chapters), it becomes necessary to transfer the ranging of the line from above to below the surface of the ground, either for making the large excavation of the tunnel, or for driving a smaller heading. When the ground is quite dry and sound, there is not always a necessity for the latter, but the excavation of the tunnel may be proceeded with at once. If, however, there be any quantity of water to contend with, as is too frequently the case, a heading at the level of the bottom of the intended work, to serve as a drain, becomes essential; and indeed, under all circumstances, a heading sufficiently large for a man in a stooping posture to pass along, will be found very convenient to ventilate the works, to form a ready communication from shaft to shaft, and to ensure accuracy in the levels and ranging, or setting out, of the work. In this way both objects were

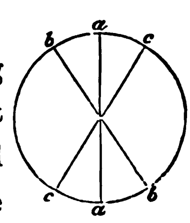
attained with the greatest certainty, at Blechingley and Saltwood; for in no one of the junctions could any deviation from accuracy be detected.

A common method of transferring the line from the surface to the underground works is by the erection of a ranging frame over each shaft; consisting of three half-timbers framed as a triangle, and supported at the angular points by stout props. In the engraving of the works above ground at Blechingley (facing the title-page), a ranging frame is shown at the shaft on the right hand of the picture, and some men are represented on the top of the head-gearing of the gin, adjusting the lines according to the telegraphic signals from the observatory. The men stand quite free from the ranging frame, lest they should, by moving it, displace the lines. One side of the frame (or triangle) is fixed parallel to the line of the tunnel, and on each of the other two sides is spiked a triangular prism-shaped piece, or block, of wood, in such a situation that a line passing over the projecting arris or angle of such block shall be in the intended line of the tunnel, and pass down the shaft as close to its side as possible, without touching the brickwork in its descent. The upper end of the line is fastened to a nail at the back of the timber, and a heavy plumb-bob is suspended below, to stretch it perpendicularly. The bob is immersed, or hung in a vessel of water, the more readily to bring it to rest, and ensure its steadiness.

The line that I used for this purpose was common fishing-line, rather larger than whipcord. I am aware that copper wire, and other substitutes, have been tried, but believe they have not generally been found to answer better than the common line, which has the advantage of presenting less temptation to be stolen. That so fine a line may be distinctly seen through, the transit at a distance, a board, having one side painted white and the other black, was held up behind the suspended line, and when the white side was turned towards the observer, the line was rubbed over with charcoal, whereby the observer had to view a black line upon a white ground; and when the black side of the board was used, the line was rubbed over with chalk, when a white line upon a black ground was presented to view. Sometimes the one, and sometimes the other, was more easily to be seen —for the shafts near the observatory the black line on the white ground

generally answered best; but for greater distances the white line upon the black ground was preferred. This might probably in some measure thus arise. The wires in the telescope being black, could not so well be distinguished on the dark surface of the board when it was near, but this effect would diminish when the board was further off; the state of the atmosphere might also have some influence on these different appearances. Two lines were necessarily suspended down each shaft, on its opposite sides; the one farthest from the observatory was usually ranged first, and then the nearer one; after which they were both presented to the observer's view at once, by way of test, when, if the previous ranging of each line separately had been quite correct, both would appear as one line; and if such was not the case, a repetition of the process of ranging each line separately took place, until the result was satisfactory.

When the signal had been given that each line was correct, a notch was cut in the vertex of the triangular block where the line passed over it, which notch represented the correct point of suspension of the line, and formed a recess for it to rest in, retaining it in its proper place. A screw with a capstan head has been applied to this purpose, which cannot readily be disturbed, as persons have been mischievous enough to alter the notches, or cut more of them, to annoy the parties who might next use the line. These screws no doubt answer that purpose very well; but where the ranging-frame is erected on a spoil-bank which is new-made ground, a continual settlement is taking place, and, consequently, a motion arises in the parts of the ranging frame which would put the best contrivance out of adjustment: therefore, as it is necessary frequently to examine the notches over which the line passes, a wooden block will be found to answer all practical purposes. The annexed cut shows the appearance of the diagonal or cross wires of telescope when bisecting the line suspended from a ranging frame. The vertical line *a a* is the ranging line, which must be moved to the right or left till it bisects both the upper and the lower angles of the cross wires, *b b* and *c c*, of the telescope.



The foregoing method of ranging the lines cannot be satisfactorily used

except in calm weather; for the wind has so great an effect in forcing the lines out of the perpendicular, even with a plumb-bob weighing nearly a quarter of a hundredweight suspended by it, that when the wind is at all high it is next to impossible to adjust them correctly, and therefore a delay from this cause will frequently take place in so uncertain a climate as ours, which is not only inconvenient, but, where the ground is heavy, may be attended with danger. I allude to a delay in setting the leading frames when the ground has been excavated ready for the brickwork. These circumstances led to my adoption, at Saltwood Tunnel, of the iron spikes with holes in them, figured and described in the next page.

When the heading or tunnel is to be commenced, it is necessary to mark, on opposite sides near the bottom of each shaft, the exact position of the intended centre line, that in advancing the works in those directions there may be a certainty not merely of *meeting* the workings in the opposite directions from the other shafts, but that the meeting (or thirl as it is called), may coincide correctly; or, in other words, when the tunnel is completed, a line stretched from end to end should pass exactly along the centre of its breadth in all parts. Such a degree of accuracy is not always attained, neither is it so essential for the heading as for the tunnel; it will be sufficient for the former if it be so straight that a line stretched along its whole length may be quite free (by a few inches) from touching its sides; but the junction of the tunnel should be strictly correct, and may be so when proper attention is bestowed in ranging the work and setting the leading frames; the latter is too often left to merely intelligent labourers, instead of being done by the Resident Engineer himself, and therefore it is not surprising that we occasionally hear of such deviations from accuracy as six, twelve, and even eighteen inches in the meeting of the work at the junctions of various tunnels. To mark at the bottom of the shafts the direction that the workings are to take, is simply the transference of the position of the lines, when suspended from above, to the sides of the shafts, by ranging, and driving spikes or nails; the lines having been previously adjusted to position, in the manner before described; or by a more simple method, as follows.

In setting the shafts for the construction of Saltwood Tunnel, I adopted a

plan which obviated the delay arising from windy weather, &c., and saved much time and chance of error afterwards: it was as follows. When ranging the intended centres of the shafts (which were nine feet clear in diameter), a substantial stake was driven or fixed securely into the ground, about sixteen feet on each side of the centre of every shaft, and over the intended centre line of the tunnel, so that when the shafts were sunk and bricked, these external stakes were about ten or eleven feet from their inner edge. On the top of each stake we drove a spike, made in the form shown in the margin (one-half the real size), and ranged the centre of the hole in the spike accurately with the transit instrument; this done, wooden caps were screwed over the said spikes to prevent their being disturbed.

The ranging of each spike can be done with the greatest precision, by holding a piece of white paper at a little distance behind it, so that the hole may present a neat white disc for bisection with the cross wires of the transit; and, by thus watching the spike as it is being driven, any deviation to the right or to the left may be corrected by the man who is driving it, upon giving him the necessary signal with the telegraph.

A line is stretched centrally across the mouth of the shaft, and its ends passed through the holes in the spikes above described; it is then to be drawn tight, and made fast. A plank should next be fixed at each side of the shaft, at right angles to the line, and so placed that one side of the plank may hang over the shaft about two or three inches, or sufficiently to keep the line clear of the brickwork when it is suspended from the said plank. The lines may next be lowered and the plumb-bobs attached to the bottom, and when steady, the lines may be moved along the edge of the plank until they hang precisely under the horizontal line which crosses the shaft; in this position they may be secured by a nail driven into the plank, and the line twisted around it.

By the adoption of the ranging spikes, as above described, it is clear that no annoyance can arise from windy weather, which so much affects the lines when suspended from a ranging frame elevated above the shaft—because they are wholly sheltered; and, if care be taken to keep the ranging spikes

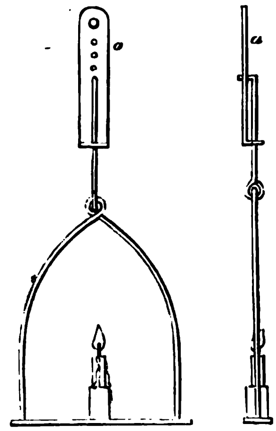
from disturbance, the lines can be dropped down the shafts at any and at all times, night or day, for setting the leading frames, or verifying the position of fixed marks: an advantage too well known to the practical man to require further comment.

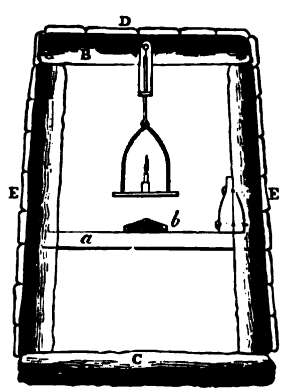
When the lines and the suspended plumb-bobs have come to rest, and are steady, nails may be ranged by them, and driven into the square timbers on each side at the bottom of the shafts; thus establishing two points in the line required, from each of which the workmen may suspend a plumb-line to guide them in keeping their work in line, and by which they may also correctly fix other nails more distant from the shafts, as their works recede therefrom.

Some attempts have been made to range the lines below by means of the transit instrument itself; for which purpose it was placed over the shaft, and having been correctly adjusted to position, &c. by some such means as have been previously described, the telescope was turned vertically downwards, whereby the observer (by standing over the instrument) might look down the shaft (the base of the stand being made open for that purpose); and thus it was supposed he might range a line, a wire, lights, enamel discs, or any other of the many contrivances which have been suggested for that purpose. Such methods are pretty in theory, but in practice not very likely to answer; for independent of the difficulty of thus accomplishing the required object, much time would be consumed, and the result not so satisfactorily arrived at as by the method of dropping the lines from the ranging frames; and less advantageous, both as to expedition and certainty, than the method by the ranging spikes adopted at Saltwood, as before described.

As the miners advance their headings, or recede from the shafts, they must fix (as before stated) other ranging points from which to suspend more plumb-lines; this they do, by looking back, and ranging them with the lines in the shaft; and from these new points they range others still more remote, to prevent their deviating from a straight line. When the works at Bleching-ley had advanced to this stage, the continual verification of the men's proceedings became necessary; and for this purpose the author contrived a candle-holder (shown in the annexed engraving), which answered ex-

tremely well. It was previously the custom, when ranging several lines at short distances apart, for a man to stand near each of them with a candle, which he shaded with one hand to keep the direct light from the observer, and to throw more light upon the line: this occupied the time of several men, and was not so satisfactory as the use of the candle-holders, which were suspended from the same nails that the miners attached their lines to. Four of these were generally used at one time, and by raising or lowering them in their racks, *a*, the flames of all the candles could be brought to the same level; and if the nails from which they were suspended were in the same straight line, all the four candles would appear but as one, when viewed in a proper direction; and, on the other hand, the least deviation from the proper line in either of the nails under trial was distinctly shown, especially in the otherwise darkness of the underground works; and therefore it could be corrected. This statement may easily be proved, by observing how correctly any number of candles, of the same height and of the same level, can be ranged in a line along a passage or corridor or even on a table. By such means the work of the miners was kept straight. The heading at Blechingley was remarkably correct: that at Saltwood was not so well done, arising from the difficulties to be contended with, as already mentioned, and which will be hereafter more fully described; nevertheless, a line could be and was stretched through the work without touching the sides, being nowhere within nine inches thereof, and therefore it answered all the purposes required.





The annexed cut shows one of the candle-holders suspended from a nail in the upper cross-piece or cap, B, of the heading frame, or 'setting,' as it is termed. The upper part, or rack, *a*—(see last figure)—was made of thin sheet iron, with a number of holes in it; the remainder was of iron wire, carrying a

socket for the candle. By means of the rack, the candle could be raised or lowered to the proper level, and being hung by a flat plate it was prevented from revolving and thereby interposing the wire in the line between the flame and the observer, which would frustrate the desired object. This position is shown in the right-hand figure of the former engraving.

As soon as the headings were driven from end to end, the permanent ranges were fixed; each consisting of a cross-piece, *a*—(see last figure)—fixed to a setting in the heading, at intervals of about thirty or forty feet, and having marked thereon where the intended centre line of the tunnel would cross, a block of wood, *b*, was screwed down, having a hole through it which was placed in coincidence with the said centre-line mark. By passing a line through these holes in succession, the centre line of the tunnel was ranged at all times. The method of determining the position of the centre marks on the cross-pieces is by suspending the vertical lines, as before described, down two or more consecutive shafts, and stretching a long line very tight in the heading; which line is then moved to the right or left, until it coincides with or is perpendicularly under the two lines in each shaft at the same time, and where the line then crosses the piece of wood, *a*, is the position for the central mark, and the hole in the block, *b*. When those marks that are near to the shafts are removed by the construction of the side and first leading lengths of the tunnel, it is convenient to fix in the invert a post of baulk timber, with an iron cap, having a similar hole to those in the blocks above named, centrally arranged, through which to pass the line when required. When these marks are fixed all the way through the heading, a number of points will be established in the centre line of the tunnel, and therefore the whole, or any portion of the work can be correctly ranged out whenever required. With such conveniences at hand, no leading frame should ever be set but by this line to denote the position of its centre. No further reference need be required to the surface or to the transit instrument; which, however, had better be kept up until near the completion of the work, or until all chance of its being again required has passed away; the observatory may then be taken down, and the materials worked up. When

however, the tunnel is to be driven without the use of a heading, frequent reference to the points on the surface will be required.

In perusing the above particulars, it will strike the reader that if the line stretched along the heading from whence the central holes in the blocks, *b*, are derived, extended the whole length of the tunnel at once, the greatest accuracy in the result would be obtained: but such a line, when the tunnel is long, would 'sag' too much and probably break before it could be strained sufficiently tight; therefore a line as long as possible, so as to answer these conditions, should be used and thus the whole length be ranged piecemeal; which having been done with care, and embracing in each length at least two of the previously-ranged centres, little or no error need arise.

The whole of the foregoing methods and details of ranging the lines were not adopted by the author at the first starting of the work; but suggested themselves from time to time, as circumstances arose. They are given as the methods he most approves, and would adopt in future, if ever again called upon to execute similar works.

THE LEVELS AND BENCH-MARKS.

Having described the method of keeping the works straight in a horizontal direction, it remains to explain that of making it correct in a vertical direction; or, in other words, preserving the proper level. When the tunnel is upon the same level throughout, the task is easier than when it is inclined; although the latter presents no difficulty, or particular chance of error, to a careful person. A section of the ground must first be made along the intended line of the tunnel, and the relative level thereto of some standard bench-mark determined for future reference. The position of the shafts having been determined upon (or even began) a substantial bench-mark should also be established opposite to each shaft, but at such a distance therefrom as to be a little beyond the area which the spoil-bank and materials used in the course of the work are likely to cover, so that it may be always accessible for reference. For this purpose, large stakes or

ends of square timber should be driven or fixed in the ground, so as not to be easily disturbed, and an iron spike with a round head driven in the top, upon which the levelling staff can be held; and they may be denoted by the same numbers—1, 2, 3, &c.—as the shafts to which they are opposite. The relative level of these bench-marks with respect to that of the Railway, at a point immediately under their opposite shafts, must be determined, and hence, by computation, its height above some given point in the tunnel may be found—(the springing or skewback of the invert was the point to which preference was given for this purpose)—and registered for after reference. Thus, at No. 3 shaft at Blechingley, the height of its bench-mark above the standard datum of the Railway section, as found by levelling, was 343·78 feet; the formation level of the Railway at a point immediately under the said shaft, as determined by the section, and computed on the intended gradient, was 249·99 feet above the said datum: therefore 343·78−249·99= 93·79 feet for the height of No. 3 bench-mark above the formation level under the centre of No. 3 shaft. But the formation level was 1·25 below the intended level of the skewback; therefore 93·79−1·25=92·54 feet for the height of the bench-mark above the intended skewback of the tunnel. This method of computation was adopted for every shaft, and registered for future use, as in the following table.

Shaft.	Formation Level above datum at Shaft.	Bench-Mark above datum.	Bench-Mark above Formation.	Formation below Skewback.	Bench-Mark above Skewback.	Staple in Shaft. Above or below Bench-Mark.	Staple in Shaft. Above Skewback.
	Feet.	Feet.	Feet.	Feet.	Feet.	Feet.	Feet.
1	250·37	320·87	70·50	1·25	69·25	− 2·23	67·02
2	250·18	330·38	80·20	...	78·95	+ 0·22	79·17
3	249·99	343·78	93·79	...	92·54	+ 2·70	95·24
4	249·81	339·64	89·83	...	88·58	+ 7·39	95·97
5	249·67	330·68	81·01	...	79·76	+ 8·61	88·37
6	249·52	334·94	85·42	...	84·17	+ 2·73	86·90
7	249·37	335·28	85·91	...	84·66	+ 5·71	90·37
8	249·21	328·85	79·64	...	78·39	+ 3·63	82·02
9	249·05	322·98	73·93	...	72·68	+ 7·35	80·03
10	248·89	317·54	68·65	...	67·40	+ 7·09	74·49
11	248·72	302·33	53·61	...	52·36	+14·71	67·07

All the dimensions connected with the sinking of the shafts may be taken sufficiently correct with the common measuring tape; but for the actual

tunnelling operations, more certain means must be employed. It is advisable, in the first instance, to fix a bench-mark at the bottom of every shaft, which shall represent the intended level of the skewback of the invert, or any other level that may be chosen. A flat iron spike driven into the timber at the bottom of the shaft, and projecting sufficiently for the level staff to be held upon, will answer very well. Having driven this at every shaft the Engineer should level through the heading (if there is one) from shaft to shaft, throughout the whole extent of his work. By this means he will prove how far he is accurate, and if as he proceeds along the heading, he fixes at short intervals similar bench-marks at the proper level for those points where they are fixed, he will have the means of subsequently checking his work as it proceeds; and will relieve himself of all doubt as to the final result of the levels at the several junctions when they may be effected.

The method adopted for transferring the levels at the surface to the bottom of the shaft (or dropping the levels, as it is usually called), is to drive securely into the brickwork on the inside and near the top of the shaft a stout horseshoe-shaped staple, the circular part of which is left projecting from the brickwork, and forms a loop for a wooden rod to be passed through to the bottom of the shaft. The height of the upper edge of the staple above the intended works below, having first been determined by means of the neighbouring bench-mark, as shown by the two last columns of the above table, is the point from which the required length of rod is to be suspended, so that the bottom of the rod may represent the level of the invert skewback, or whatever other level may been have fixed upon. An iron gland is attached to the rod, at the proper point, which gland is larger than the loop-hole of the staple, and therefore rests upon it, and suspends the rod as required.

The wooden rod above spoken of must, from the great length required, consist of a number of pieces which are attached to each other by various contrivances; some of them have been made to screw together, precisely as the old-fashioned round legs of a spirit level were joined in their middle; but, having previously witnessed considerable inconvenience and loss of time by this method, I caused my rods to be connected with a spring catch, or

hook and eye nearly similar to the hooks we used for suspending the skips from the windlass ropes for the purpose of lowering them down the pits.

The annexed engraving shows the rods used upon the works, their connecting hook, and the gland. The rods are shown by the left-hand figure, with the gland attached at the point B. The upper right-hand figure shows the hook, the corresponding eye, and the ends of the rods to one-half the real size. The lower right-hand figure shows the form and make of the gland; A A are the cheeks which clasp the rod; C is the screw for tightening or releasing them, which screw is worked by a handle, D, similar to that of a vice; B is the hinge by which the cheeks open to clasp the rods, and when open the screw C is drawn quite out of the socket.

The rods were made ten feet long from the inner edge of the loop or eye, at one end, to the inner edge of the hook of the other, or from the two points of connection; and when they were suspended in the shaft, each ten-feet rod became as it were the link of a chain, consequently the whole would be sure to hang perpendicularly, which was not often the case with those that screwed together. Each rod was numbered for convenience in use, and was hooked on the top of the one previously lowered; number 1 having been first lowered, the succeeding numbers showed how many tens of feet had been passed down through the staple; thus, when number 6 was hooked on it was evident that 50 feet of rod were already down; and when any odd number of feet and decimals of feet had to be suspended from the staple, as for instance 95·24, the nine rods were first lowered, and upon the tenth the odd 5·24 feet was marked, and at that point

the gland was screwed to clasp the rod firmly, the under side of the gland coinciding with the said mark; the tenth rod was then hooked on to the ninth, and likewise passed down until stopped by the gland resting on the staple, and the whole then hung perpendicularly.

In all cases, both at Blechingley and Saltwood Tunnels, when the rods were suspended in the shafts, the bottom of No. 1 rod represented the required level of the invert skewback (or springing of the inverted arch), which was the standard there adopted, and for the greater convenience of transferring the said level to any other point, as a ground-mould or bench-mark purposely made, the lower three feet were graduated exactly as the levelling staff was divided; the rod was then illuminated with a candle wherever the line of sight of the level cut it.

The method of transferring levels from one point to another being so simple an operation, the reader is doubtless well acquainted therewith; and therefore no further explanation of that matter is required. In all instances the rods were suspended at least three times down every shaft; first, for establishing a number of bench-marks through the headings, as before stated; secondly, for setting the ground-moulds for every side length; and thirdly, when the shaft lengths were completed, to fix an iron bench-mark in the brickwork exactly at the proper skewback level, at the side of the tunnel under each shaft; for although the skewback at that place had then been built and completed, yet it was considered necessary to fix a proper point on which to hold the levelling staff at the exact calculated level, for the brick-work (however well done) would be almost sure to vary a small quantity therefrom. These bench-marks consisted of flat iron spikes, projecting about an inch from the wall into which they were driven; and from these standard skewback levels all the subsequent ground-moulds were set, making the calculated allowance for the rise or fall of the gradient; which would be unnecessary where the tunnel is to be constructed on the same level throughout.

NOTE TO CHAPTERS II. AND III.

BY W. D. HASKOLL, C.E.

It is not without considerable hesitation that, as Editor to the Second Edition of this very valuable work, I venture to make the few following remarks on the preceding chapters; the more so that many serious and fatal errors have arisen when the methods laid down have been deviated from, without great care being at the same time bestowed on the work; errors to remedy which have caused a great loss of time and considerable expense.

As regards the transit instrument and the observatory, it may be observed that where the length of tunnel is not very great, the transit theodolite of six inches diameter, as now constructed, may be used instead; nor is an observatory always absolutely required, if a calm day be chosen for the operation of setting out the longitudinal centre line.

Let the centre line be carefully ranged out with the instrument by means of stakes, fixing the centres of the shafts, and the stakes required for the spikes mentioned in Chapter III. and also some two or three stakes driven close down into the ground, so that the theodolite may be placed over them; into each of these latter stakes let a small brass-headed nail be driven, and let these nails be ranged with the utmost care by means of the instrument; these latter centres being thus carefully ranged, their perfect accuracy may be tested by removing the theodolite to these central points, one after another, at the same time examining the correctness of the position of the spikes.

If all things have been properly prepared for doing this, and if all has been kept in perfect readiness for carrying out this operation, it will be evident that no very great time will be required.

Let this be considered as merely preliminary, and on the first calm day let the theodolite be carefully set up over one of the stakes with the nail driven into it, selecting one that will command the best position so as to range backwards and forwards over the whole length of line, and also obtain a view of the two *distant* points that range with the centre-line; this being done, let

the *centres* of every stake, those with the spikes on each side of the shafts, as well as those into which the nails have been driven, be all carefully verified.

If this be carefully done, and the centres be found correct and thoroughly in one visual line, as seen through the telescope, there will be no fear but that a perfectly straight line has been obtained ; and the lines being strained from spike to spike over the position of the shafts will secure a correct position for the plumb-lines to govern the central line for driving the heading.

As the shafts are sunk and the headings are being set out, it is again necessary to verify the central position of the plumb-line ; and this after the earth has been raised round these shafts, so that the banks are too high for the lines hanging from the curbs to be seen with the theodolite ; their correct position may at any time be tested by the theodolite in the following manner, and, after the observations that have been made by the talented and experienced author of this work, it will readily be seen that too much care cannot be bestowed in fixing the centres given by these plumb-lines with the utmost caution, inasmuch as it is entirely by these that the central line of the heading is determined.

Then to test this after the shafts have been sunk to their proper level, let a few light triangles be constructed so that the said plumb-line may be appended from them, and let these be set up approximately over the centre line ; let the lines be stretched from spike to spike, and the plumb-lines from the triangles be made to coincide with them ; let the theodolite be set up over one of the brass nails above mentioned, and let it be observed whether the plumb-lines range true with the centre line set out, when the optical axis of the telescope ranges true with the *distant* objects already mentioned, or with one of them and as many of the little centre discs on the spikes as may be visible from the station when the theodolite is set up.

By these means it will often be found practicable to avoid the necessity of an observatory and transit instrument ; in these days of economical railway construction every item of expenditure has to be carefully guarded against as much as is consistent with safety ; where, however, the tunnel is of great length, the transit and the observatory should be resorted to for the security

of both the contractor and the company, and for the satisfaction of the engineer.[1]

Shafts and Heading.—Frequently the positions of the shafts, instead of being set out on the longitudinal axis of the tunnel, are ranged on a parallel line at a distance of from about forty to forty-five feet. When this is the case, cross-headings are driven from these shafts to the axis of the tunnel in order to drive the main heading. It will at once be perceived that this operation will add considerably to the difficulties of ranging a perfectly straight line under ground, coinciding with the longitudinal axis of the tunnel, but there are circumstances advantageous to this mode of proceeding; during the construction of the works there is less danger arising from anything falling accidentally down the shafts, the cross-headings form convenient receptacles for the tools or materials, and after the construction of the works, they are so many sanctuaries for the retreat of workmen engaged on repairs or maintenance of permanent way, or for the deposit of tools, if they are at first driven at a sufficient depth.

The bottom of the shafts may also be sunk to a depth of from two to four yards below the level of the lower level of the cross-headings, and a platform laid over this extra depth in continuation of the footway of the heading; it forms a convenient drainage or well for the water, from which it may be pumped up.

When these side-shafts are resorted to, it is evident that the same means are to be resorted to for ranging or setting out as those already mentioned, with the exception that the operations are carried on along the line parallel to the longitudinal axis of the tunnel; the *horizontal* distances between these two lines will require setting out with minute care, and with rods made on purpose; the new line being ranged, distant objects must be set up to determine its position in the most accurate manner possible; a standard measurement of the rods should be established somewhere on the ground, in order that their lengths may be tested when they are afterwards used in the underground workings in order to set out the true horizontal distance between

[1] An account of the levelling and ranging of Clifton Tunnel, in the manner ordinarily practised, is given in a subsequent chapter on Tunnelling in Hard Rock.

the centre line and the parallel line, from the centre of the shaft at bottom to the longitudinal axis of the tunnel. No small amount of care will also be required in making all these distances truly rectangular with the centre and parallel lines. The reader will not fail to remark that the Blechingley and Saltwood Tunnels presented very serious difficulties in their construction, traversing most treacherous strata, which yielded vast quantities of water; where in the construction of future tunnels similar conditions obtain, very nearly the same or quite analogous means will have to be observed; greater experience will nevertheless reduce the expense of the works. Fortunately, however, more favourable soils often present themselves to tunnelling operations, and less expensive means may be resorted to for carrying on the works.

CHAPTER IV.

SHAFT SINKING.

THE TRIAL SHAFT AT BLECHINGLEY TUNNEL.

The construction of the Blechingley Tunnel commenced with the sinking of two trial shafts, to ascertain the character of the strata through which the tunnel was to pass. Instructions for their commencement were given on February 1, 1840, and on the 3rd a contract was made with two men to sink and brick the shafts in question. They were to be 6 feet diameter in the clear; the brickwork to be 9 inches in thickness; the bricks to be laid all headers, properly breaking joint, and to be set in the best greystone lime mortar.

The situation of the trial shafts was the same as that of the working shafts Nos. 1 and 10—fig. 1, Plate I.—as they were subsequently enlarged to 9 feet diameter to make working shafts of them. They were designated as the western and eastern trial shafts, No. 1 being the western, and the other—which afterwards became No. 10—the eastern. They were both commenced on February 7, 1840, and on the 10th the western shaft was sunk 14 feet, and the eastern 8 feet. My memorandum on that day was as follows:—

'*At present the earth shows no indication of water below the first six feet; it is a kind of marl, of a slippery or greasy feel, something resembling fullers' earth.*'

On the 12th, the western shaft was sunk 25 feet, when it was no longer safe, or scarcely practicable, to proceed without inserting the brickwork, as the last six feet had yielded a considerable quantity of water. Moreover, by exposure to the atmosphere, particularly if any damp was present, the ground slaked, or rather dissolved, accompanied with a swelling or heaving move-

ment. This was invariably the case throughout the subsequent operations. It was unsafe to leave a face long exposed to atmospheric action, as such heaving brought a great weight upon the work, and in a few cases, where the excavated lengths remained longer than usual for the brickwork, the weight became such as to break the bars; which, on this account, were provided of large dimensions, averaging 14 or 15 inches diameter for the crown, and 12 inches for the side bars, all of oak. The brickwork was commenced upon an oak curb fairly bedded on the bottom of the excavation, and set level; the inner diameter of the curb (or ring) was that of the intended shaft, 6 feet; its width 9 inches, to carry that thickness of brickwork; and its depth, or thickness, 3 inches. It consisted of several pieces, connected by half-lap joints, having an iron plate crossing the joint on each side of the curb, and secured by four bolts, which passed through the timber and both of the iron plates. Upon this curb the brickwork was carried up to the surface, being well packed and rammed with dry earth, wherever there was a vacancy at the back, to make it solid.

By the time the brickwork was finished, about 14 feet of water had accumulated in the shaft, which had to be drawn out before the work could be resumed. When the sinking had advanced 2 feet further, a bed of hard calcareous sandstone, about 1 foot in thickness, was met with; this required blasting, and it was separated from a still harder rock below by about 1 inch of sand; this lower rock proved to be 2 feet in thickness; next followed 8 inches of brown sand, and 3 inches of bluish-grey sand; after which the clay or shale, the same as that we passed through above the stone, reappeared. It was expected that the stone formed a regular bed in the above situation, where it would have given considerable trouble, as it was nearly level with the top of the tunnel; it however occasioned only a temporary difficulty, as it soon disappeared, probably from some dislocation of the strata, as the hill was full of faults, and had undergone great derangement. This was evident from the strata lying most abruptly in all directions, as was strikingly shown in the open cutting at the west end of the tunnel, and mentioned at page 16. It is probable that the rock was an outlyer from the lower bed of the Lower Green Sand; the Weald Clay, in

TRIAL SHAFT AT SALTWOOD TUNNEL.

The first operation, after setting out the centre line of the tunnel, was to sink a trial shaft, to ascertain the character of the strata beneath the surface; this was commenced on April 25, 1842, and was situated 13 yards from the centre line of the tunnel, on the south side. It was originally intended that it should not only be a trial shaft, but was to have been sunk (if possible) so deep as to answer the purpose of a well, to supply the works with water during their progress, in the event of a deficiency of that article.

The shaft or well was 6 feet diameter, clear of the brickwork, which was 9 inches thick, the bricks being laid all headers. The sinking was attempted by means of a barrel (or drum) curb, which upon being undermined descended by its own weight and that of the brickwork (which was constructed upon the curb, and was carried up as the curb descended). In this manner a depth of 46 feet was attained, when the drum getting a little out of the perpendicular, it stuck fast and could be got no lower, and after a fruitless attempt to liberate it, it was left in its place, and the sinking resumed beneath in the ordinary mode to a further depth of 20 feet 6 inches, when, coming upon a quicksand, we were unable to prop up the brickwork during the process of underpinning, and therefore could proceed no further by that method. Another curb was then constructed of the same diameter as the inside of the shaft, namely 6 feet, to continue the sinking from within the completed brickwork; but so large a quantity of water was given out, that 8 feet additional depth only were attained, making a total of 75 feet down.

The drum curbs, and the mode of using them, will be understood by reference to the section (page 57) of part of the shaft; which shows the first curb A in the position where it became immovable; the termination of the larger portion of the shaft at B; and the smaller curb C at the bottom of the shaft. The curbs were made smooth on the outside, that they might slide down easily; were strongly bolted together, and the bottom edge formed like a wedge (or knife edge) to avoid resistance. Two plumb-bobs were suspended at right angles to each other, in the curbs, to guide the workmen in

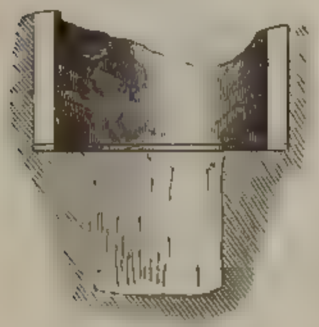
keeping them perpendicular. As the brickwork descended with the curbs it was continued upwards to the surface of the ground; thus constantly increasing the load upon the curb, and of course its tendency downwards, as the earth was removed from beneath.

There are various opinions as to the advantages derived from the use of barrel or drum curbs (running curbs, as they are sometimes called) over the ordinary mode of propping and underpinning. The latter mode is more generally adopted where the ground is sufficiently solid to carry the props in safety; in all other cases the drum curb may be advantageously employed; but it requires much care to prevent it from setting fast, as it did at Saltwood, which may principally arise from its getting out of the perpendicular, either from carelessness of the excavators, or from the earth yielding on one side; neither does it appear that the work can be more expeditiously done by its use. On the other hand, there is apparently a greater degree of security to the workmen, who being employed within the drum may perhaps be somewhat less exposed to danger; but this is even doubtful.

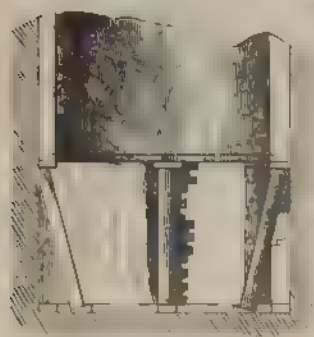
The following particulars of the method of shaft sinking by props and underpinning may not be uninteresting:—

The shaft is first sunk to the full diameter of the outside of the intended brickwork, and as far down as the earth continues to stand safely. When it is no longer prudent to proceed, a timber curb or flat ring is laid upon the bottom of the excavation; this curb or ring has its inner or clear diameter the same as the intended shaft, and its external diameter as much greater as twice the intended thickness of the brickwork, for upon its flat surface the bricks are to be laid. The curb should be made of durable timber, as oak, and formed in several segments, joined with half-lap joints, secured with a plate on each side, and four bolts passing through the whole; upon this curb the brickwork is carried up to the surface. The sinking is then renewed by

excavating the earth from the centre of the shaft, as far down as may be consistent with safety, leaving a benching of earth to carry the shaft, as



shown in the annexed engraving; a narrow portion of this benching is next cut away as far back as the brickwork, and a prop inserted raking either to the front or back of the intended brickwork; if to the front, the prop can be saved and used again, but it is sometimes necessary to place them raking behind the brickwork, in which case they are built in and lost. Another prop is then similarly inserted, and so on until the whole curb and brickwork is thus supported. When this is done another similar curb is inserted perpendicularly under the upper one, and the brickwork carried up to meet or underpin it. The work during this operation presents the appearance shown in the following sketch. The props, however, are all shown as raking inwards: one advantage in their raking outwards is that they leave more room for the



bricklayers to work. The props may also be set perpendicularly under the upper curb, and the brickwork completed between any two props before they are removed; or the work may be quartered in (that is, a quarter completed at a time). Other methods of proceeding are also occasionally resorted to. The props must rest upon a broad base, or foot-blocks, and be securely chocked to the curb above, to prevent motion taking place. As the brickwork proceeds, all vacuities behind should be rammed solid with dry earth.

In sinking through, and constructing shafts in the shingle beach upon the sea coast, at high-water mark, and also about midway between high and low water marks, the following method of proceeding was found to answer. Having cast out the shingle and sand to a depth of five or six feet, or as far as conveniently practicable, a stout timber curb was laid level upon the bottom of the excavation, and upon this was built about four feet of brick-

work, in cement; then, during the intervals of the tides, the shingle was removed from under the curb, by workmen within the shaft, and as they so removed it, the shaft gradually descended by its own weight, and the bricklayers continued to build it upwards, so as always to keep it above the level of the beach around; which otherwise would have filled the shaft at each high tide, and have occasioned great loss of time in its removal. This operation is similar to the sinking by means of a barrel curb, before described; but which would not answer so well in such loose material as that on the sea-shore, as it is capable of doing in firm soil.

On another occasion, the author was required to obtain fresh water for the supply of a large building erected on the sea-shore, to be used as an hotel. The spot where the building was erected had been left by the sea not many years before; the recession of the water—or rather the accumulation of shingle—having been occasioned by the construction of a pier, for commercial purposes, extending into the sea close by. Upon an examination of the locality it appeared clear that within seven or eight yards from the surface, the top of the middle bed of the Lower Green Sand stratum would be found in situ; and therefore there was a reasonable probability that a supply of fresh water could be obtained from that level. But whenever a hole was made in the ground, which consisted of the beach and sand originally deposited by the sea, the salt water appeared and disappeared with the rising and falling of the tide, the sea percolating through the beach (which was there seventeen feet deep), and rising in the hole to the level of the tidal water. Under these circumstances it was necessary to sink a shaft that should be water-tight, effectually to exclude the sea water from entering, and to prevent the fresh water that might rise in it from escaping; accordingly, a large shaft was first sunk, protected around with timber, by having square frames or settings at intervals of about three feet, and behind these, or between them and the earth (or beach), upright planks were driven close to each other, in the manner of sheet piling, some men driving at top while others were removing the earth from under the piles; this method was followed quite through the shingle, and answered well, but it could only be proceeded with at the time of low tide, as otherwise the salt water filled the

timbered shaft. In a manner very similar to this, the difficulties in shaft sinking at Saltwood Tunnel were conquered; as will be explained in a subsequent chapter.

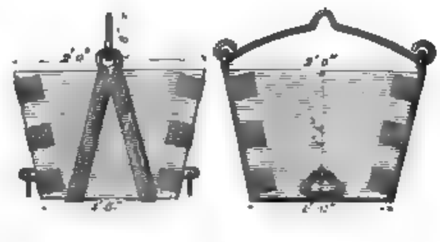
The timbered shaft was sunk quite through the beach and silt, and at eighteen or nineteen feet down the middle bed of the Lower Green Sand was reached; when, as was expected, a large supply of fresh water was found, precisely in the same geological level as the water was met with in sinking the shafts at Saltwood. The brick shaft or well was then commenced upon a timber curb, sunk into the stratum about three feet below the bottom of the shingle, and nine-inch brickwork in cement carried up to the surface, and between the outside of the brickwork and the timber of the shaft the space was rammed with well-puddled clay from the bottom to the top—the planks being left in the ground, lest their removal should disturb the puddling, and endanger the letting in of the salt water. The fresh water was admitted into the well through three pipes, which were built in the brickwork near the bottom of the shaft; but a short time afterwards, the pressure of an extraordinary high tide enabled the sea water to reach these pipes, and thus make the well-water brackish; whereupon the pipes were closed up, and the whole of the water from that level excluded, and by means of boring at the bottom of the shaft, a plentiful supply of pure water was obtained, which rose in the well to within four feet of the surface of the ground.

DESCRIPTION OF THE SKIPS, ETC.

The common windlass, or jack-roll, as shown placed across the top of the shafts, in Plate II., was the only machinery employed for raising the earth and lowering materials, throughout the sinking and heading-driving at Blechingley. The gins (or whims) were not erected until the actual tunnelling operations were commenced; when more powerful means had become necessary. The same windlasses, &c. were subsequently employed in sinking at Saltwood Tunnel, but were there obliged to be laid aside before the sinking was completed, on account of the great flow of water requiring more efficient means to keep it under, as already explained.

As the windlasses were adapted for manual labour, a smaller quantity of

earth could only be drawn up at one time than was subsequently raised when horse power was employed. The most convenient sized skip to be used with the windlasses is represented in the annexed engraving. They were made of inch elm, and weighed 84 lbs.; but when filled with wet earth, as that at Saltwood, weighed upon an average 500 lbs., and required four men to raise them. The skips were attached by their bales to the ropes, by



means of a hook, which, at the same time that it afforded facilities for releasing it, both at the bottom and top of the shaft (the former for filling the skip, and the latter for emptying it), was contrived so as not to be liberated during its ascent or descent, as such an accident would be likely to prove fatal to the men below. Several schemes were tried for this purpose, and the two found to answer best are shown in the annexed engraving; wherein both a side and end view of each are given. The left-hand hook is secured from unshipping by means of an iron pin passed through the return of the hook above a loop dropped over for the purpose; and the right-hand figure shows how the like security was ob-

tained, by a spring acting against a continuation of the hook, which is thus converted into a ring. This is very similar to the hooks of the hanging-rods represented at page 46. The real dimensions both of the skips and the hooks are given in the above cuts.

At a subsequent period of the work, when the gins were set up and horse power applied to raise the earth, the large-sized skips were used. These are represented in the following engraving, where the real dimensions are also given. These were not suspended from the rope by a bale, as were the above described for the smaller skips, but the iron bands terminated in loops or eyes, one on each of the two opposite sides of the skip, as at A, A. These loops received the hooks of a chain made of ⅝-inch iron, that was attached to

the end of the rope by a shackle, which is represented at page 80, where the method of suspending the water barrels is described. The wheels and axles are attached for the purpose of running the skips along a temporary

railway laid underground from the several faces of the work to the shaft, and also upon a similar railway, above ground, from the top of the shaft to the tip of the spoil-bank, where the earth raised was deposited. There was no necessity for such an appendage to the smaller skips, because they had to be removed but a few feet, either below or above, and were sufficiently light to be easily shifted by hand: on the contrary, the large skips were too heavy for men to move about, except upon wheels; and the distances they had to be moved continually increased as the work advanced. They were made of 1¼-inch elm; and when empty weighed 140 lbs., and when full of wet earth 1,050 lbs.

DESCRIPTION OF THE HORSE GINS.

The following engravings represent the horse gin (or whim) that was employed upon the works. Fig. 1 is a longitudinal view of the gin at work; and fig. 2 shows the same machine as it appears in the other direction, or at right angles thereto. The letters of reference in each apply to the same parts.

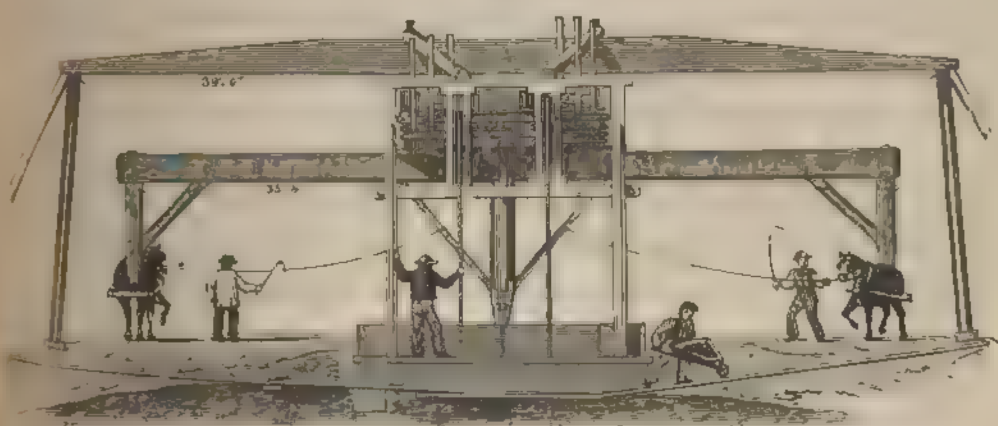
A is the span-beam, with a bearing of 39 feet; 16 inches in depth in the middle, and 8 inches thick. B is the horse arm, 35 feet 8 inches long; and, as first made for the Blechingley works, consisted of one piece, 12 inches by 7, passed through a mortice in the drum shaft, D. But finding this mode of construction to be too weak to stand the strain for a length of time, the

horse arms were subsequently trussed, and consisted of two pieces, each 1 foot 2 inches by 4 inches, notched into and bolted to two opposite sides of the drum shaft, D; where they measured across, from outside to outside, 2

FIG. 1.

feet; and then the truss was gradually narrowed near the ends, where they measured 1 foot 4 inches, and were blocked apart, and bolted together through the blocks, between the centre and the extremities. C is the drum, 9 feet in diameter, and 2 feet 6 inches deep, divided into two parts by a fillet

FIG. 2.



round the middle of the cylindrical part of the drum, to separate the ascending and descending ropes. The ropes were prevented from working off the drum by horns projecting around the top and bottom, twelve in number,

made of 4 by 4-inch stuff, and jutting out about 10 inches; the inner side of the projection being sloped off. D is the drum shaft, 13 feet 6 inches long, and 1 foot 2 inches square: to this the horse-arm is securely bolted at 4 feet from its top, and steadied by stays of 4 by 4-inch scantling, from its lower part; to these stays the driving boys tied one end of a small cord, which served as a rein to the horses, as shown in the engravings. Above the horse-arm, and resting on it, the drum was secured by the shaft passing through it; the frame of the drum was made square in the centre for that purpose; the lower frame of the drum was steadied from the shaft at right angles to the horse-arm, by stays, similar to those last described. The shaft rotates on two spindles of 2-inch round iron, one end being squared and turned both ways, at right angles, to secure a firm hold in the shaft. The top spindle worked in a socket formed by straps bolted to the span-beam, and the bottom spindle worked in a bell-metal cup. The top of the shaft had one hoop, 2 inches by ½-inch, driven on after the spindle was fixed; and the bottom of the shaft in like manner had two hoops. The weight of the top spindle was 28 lbs.; the bottom spindle, 25 lbs.; the straps for the top spindle, 18 lbs.; the three hoops, 21 lbs.; and the brass or bell-metal cup, 13 lbs.

The horses were harnessed to shafts attached to a perpendicular piece, 8 inches by 10 inches; its top forming the end of the truss of the horse-arm, from which it was pendant: it was also steadied thereto by means of braces, as shown in the engravings. The harness shafts were made to revolve on a spindle at the bottom of the perpendicular piece last named, whereby the horses could be turned round, and proceed in the opposite direction, to reverse the action of the machinery, which was necessary at every ascent and descent of the ropes,—the one ascending as the other descends, and *vice versâ*. It would, however, have been more convenient had the machinery of the gin been so contrived that the alternate ascending and descending action of the ropes could have been effected without the necessity of turning the horses round.

The span-beam, A, was supported at each end by a triangular frame—shown in the last engraving—the base of which was 13 feet long, and was steadied with props. E is the pit frame, placed on each side of the shaft, at

a distance of 24 feet 6 inches from the drum-shaft. This carries the head-gearing, or frames, in which are mounted the pulley wheels or sheaves, which were of cast iron, 3 feet in diameter, and weighing 1 cwt. 3 qrs. The spindle upon which the sheave revolved was of wrought iron, 2 inches diameter; and worked in a bell-metal box, or plummer-block, weighing about 3½ lbs. K was a pole, of which there were two, called jackanapes poles, because they carry what are technically called the jackanapes, G, G, whose use was to keep the rope straight in passing from the drum to the head-gearing, and had small friction rollers for it to work upon. These jackanapes were pendulous, and therefore they vibrated or yielded as the ropes moved; which was necessary, because the ropes continually changed their levels as they wound round the drum, or *vice versâ*.

H shows the trough into which the water barrels emptied themselves when tilted, as described at page 80; from which trough the water was passed into proper drains, and was not allowed to soak into the ground. I shows the platform, made to run upon flange wheels, which worked upon rails, whereby it could be drawn over the shaft to cover it when necessary, for greater security in landing the skips full of earth, as they were raised to the surface; the skips were then rolled away, on temporary rails, to the spoil-bank, and emptied of their contents. But when the wet earth was brought up, at Saltwood Tunnel, during the sinking and water drawing, it was generally emptied into barrows, and wheeled away. This was being done when the sketches for the foregoing engravings were taken, and which accounts for their being shown therein.

The pit frame and head-gearing were made of oak; the frame of the drum of oak, and the covering of elm; the jackanapes poles were of larch; the horse shafts of ash; and the rest of the gin of Dantzic timber.

For the greater preservation of the ropes, they might be tarred, and payed over with coarse canvas tarred. Some such covering is requisite for economy's sake, as the wear upon the rope is considerable. It may be worth remarking that wire ropes would in all probability be applicable to the purposes now under consideration, not only on account of their apparent greater durability, but to prevent the possibility of wicked persons cutting or

otherwise injuring the ropes to cause accidents by their breaking when loaded. Such a circumstance occurred at Balcombe Tunnel, upon the Brighton Railway; where a rope having wilfully been cut, broke at a time when several men in a skip were suspended by it; whereupon they fell to the bottom of the shaft and one of them was killed. This, unhappily, is not a solitary instance, as the same kind of injury was done to one of the ropes at Blechingley Tunnel, but was fortunately discovered before it was again put into use. Too great care cannot be exercised where there is so large a body of men congregated together; and some of whom are too apt to indulge vindictive feelings from motives of revenge.

CHAPTER V.

SHAFT SINKING, CONTINUED.

EXCAVATING AND CONSTRUCTING THE WORKING SHAFTS, AND SUPPORTING THE BRICKWORK BY SHAFT-SILLS AND HANGING-RODS.

The working shafts were 9 feet clear diameter, the brickwork 9 inches in thickness; an oak or elm curb was inserted at the bottom of every length of brickwork as it progressed downwards, and at the bottom of the brickwork, where the square-timbering of the shaft commenced, a curb of 4 inches in thickness was used; the upper ones having been but 3, or $3\frac{1}{2}$ inches. These were to remain permanently in their places. As the sinking proceeded, notes were taken of every change of strata, which, at the same time that they were interesting as geological facts, were occasionally useful afterwards. For instance, in sinking the trial shafts at Saltwood, we passed through a stratum of clean sharp sand, well adapted for gauging with cement. In the course of our subsequent work such sand became a desideratum, and all we had to do was to break through the brickwork of each shaft, at the particular level pointed out by the memoranda, and a man threw down into the tunnel as much as was required, excavating it as a driftway. Thus a plentiful supply of excellent sand was obtained at a cheap rate.

Plate II. shows two sections of a shaft at Saltwood Tunnel, fig. 1, at right angles to the tunnel, and fig. 2 in the direction thereof; the plan adopted for suspending the brickwork and square-timbering the lower part of the shaft is therein represented; likewise, the brickwork and the timber rings, or curbs, at *a a*, &c., at the bottom of each length. The windlass, together with the skips for raising the earth and lowering materials—the one ascending as the other descends—are also shown. The skips were suspended from

the rope by a particular form of hook, that prevented their unshipping in case of striking against each other in passing, or against the sides of the shaft. A further description of the above will be given in a subsequent chapter.

The following is a copy of the specification drawn up for the guidance of the bricklayers in constructing the shafts at Saltwood Tunnel:—

The brickwork of the shafts is to be nine-inch work, laid all headers. The shafts are to be nine feet clear diameter, and to be constructed truly cylindrical and perpendicular. The whole to be laid in mortar composed of one part of stone lime and 2¼ parts of clean sharp sand, well mixed up with a proper quantity of water; the lime to be sifted before it is made into mortar. The mortar-joints to be sufficiently thin to make four courses of work not exceed one foot. The back of the work to be rammed and well punned, course by course, as the work proceeds, so that it shall not be possible to drive the bricks back from their places by applying any moderate force. Each brick to be dipped in water previous to its being laid. The bricklayer to find all tools, sieves, tubs, &c.; the engineer to find bricks, lime, sand, and water.

SUPPORTING OR SUSPENDING THE SHAFTS.

The brickwork of each shaft was carried down to within a few feet of the intended top of the tunnel; and from thence through the space intended for the tunnel; the shaft was continued by means of timber only, having square frames or settings, at short intervals of depth, and close planking against the sides of the excavation, the square settings being supported from each other with props of round timber (all of which are shown in the two sections, Plate II., and in fig. 1, Plate III.). This timbering was adopted to facilitate the subsequent excavation, which could not have been so well done if the brickwork had been continued to the bottom. The square-timbering, however, will be explained next in order after the present subject.

The brickwork of a nine-foot shaft forms a cylinder of great weight, as it contains 3 tons 7 cwt. to every yard in depth, and the friction of its circumference against the earth is not sufficient to resist its tendency to slide

down when the ground is removed from under it to construct the tunnel. It is therefore usual to support the shafts by some means until that portion of the tunnel immediately beneath them, commonly called the shaft length, is completed. The shafts are then permanently connected thereto by a curb of cast-iron or brickwork, as shown in figs. 1 and 2, Plate V., and thus made secure.

The shafts may be secured until they can be permanently united to the tunnel, either by supporting them below, or suspending them from above. At Blechingley the former plan was adopted, and under each shaft was fixed, at right angles to the direction of the tunnel, a pair of sills formed of whole balks, fifteen inches square and thirty-four feet long; and upon them was fixed a square frame of the same kind and scantling of timber, to carry the bottom ring or curb of wood, and the superincumbent shaft. The under side of the sills was placed three feet above the top of the intended brickwork of the arch, that the miners might have plenty of room for their bars, &c. in excavating for the side lengths.

In consequence of the gradient of the railway at this place being lowered after the shaft-sills were fixed, they necessarily were so much higher above the top of the tunnel: this, however, was attended with but little inconvenience.

Fig 1

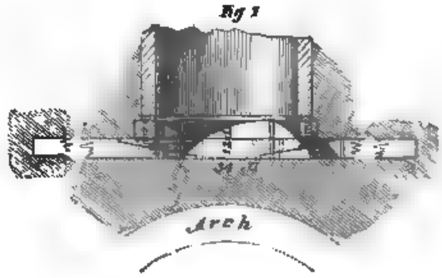
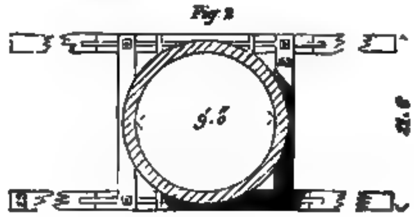


Fig 2



The annexed engraving shows the sills and the square frame in detail, with the bottom curb, and shaft resting on them. Fig. 1 is a section of the lower part of the shaft, and fig. 2 a plan showing the shaft resting on the square frame that is supported by the sills. The shafts being but nine feet in diameter, the sills were scarfed in two places, that they might form three pieces, for convenience in lowering and fixing them. These scarfings, together with the glands that connect the square frame with the sills, and the necessary iron plates and bolts are shown in the two figures.

For the insertion of sills, small headings were driven each way from the shaft, no larger than was sufficient for a man to work in; and when the sills were properly placed, and the square frames attached and screwed down by the glands, and the bolts passing through both the square frame and the sills, the headings were filled with the earth previously excavated, and rammed solid; a good bottom curb was then placed on the frame, and the brickwork made good to underpin the part of the shaft previously constructed, and thus the whole shaft rested on the sills.

In Plate III. the sills and frames are shown as fixed; at fig. 1 they appear in the direction of the tunnel; at fig. 4 at right angles thereto, *a* the sills, *b* the frame. The sills are also shown in each of the figures in Plate IV., and in figs. 1 and 2, Plate V.; the last two show their appearance and position when the whole was completed.

The stratum of earth through which for the most part the shafts were sunk at Blechingley was a hard blue bind (or shale) so highly indurated as to be when first exposed like rock, which required to be blasted for the economical working of it. A mass so compact was capable of bearing the weight of the shafts by means of the sills, when the ground beneath was cut away for the shaft length, as shown at figs. 1 and 2, Plate IV. Some assistance, however, may mostly be obtained by means of props from the bars of the shaft length, and from the projecting ends of the crown bars of the side lengths, as shown at *a*, *a*, *a*, &c. figs. 1 and 2, Plate IV. But in all cases where the ground is not a solid or compact mass, when for instance it is loose (or quick) sand, as was the case at Saltwood, the use of shaft sills is injurious rather than beneficial, because the ground having no cohesion in itself cannot form a foundation for the sills to rest upon. Under such circumstances they would require to be supported, and thus produce a source of difficulty and danger of no small magnitude: this may be fully understood by reference to Plate IV., fig. 2; for if the ground at *b*, *b*, was loose sand, it would be liable to give way under the sills when the excavation was made for the tunnel.

These considerations led to the omission of the sills for the shafts at Saltwood, and to the suspending them from the surface of the ground by means of hanging-rods, which are generally made of bar iron; but there

being no suitable material of that kind on the ground, and for the sake of economy, these were constructed of wood, as shown in Plate II., where both a front and side view of the hangings is given, and their construction rendered plain. A square frame of whole timber under the brickwork was carried by the hangings, and was sufficiently stout to prevent any unequal settlement of the shaft.

The timber of the hangings was larch, of a good quality, being the only available material at hand; and the pieces were scarfed together to obtain the proper length, as shown in the figures, Plate II.

In most of the shafts the hangings stood the pressure without exhibiting any apparent deficiency of strength; in one or two they appeared weak for the work; and in one case they broke, or rather tore away at the scarfing, but having shown previous indications of so doing, any casualty was stopped by timely propping.

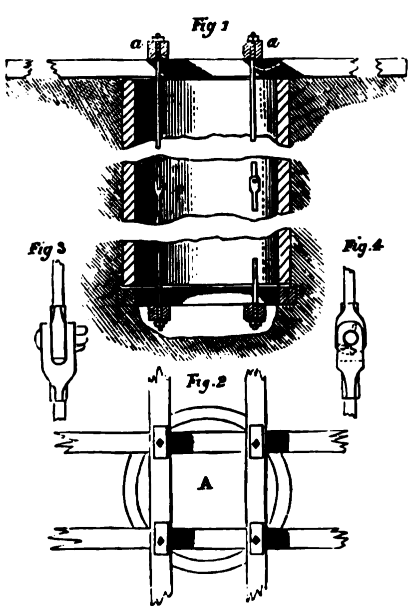
This apparent weakness and breakage was chiefly attributable to the following cause:—It has been stated that the work was being done through loose sand, the ground having in the first instance been saturated with water to a very great extent; when the water was subsequently drained therefrom the ground was left in a porous state, and yielded in all directions before any pressure; and where the lower parts of the shafts were sunk and square-timbered, a great quantity of what was then a quicksand ran into the shaft, and was removed with the water, leaving large vacuities or caverns in the vicinity, which were unknown to us, and therefore to the great peril of the shaft so situated, for a small amount of lateral or unequal pressure would then throw an unfair strain upon the hangings. This was probably the cause of the apparent weakness in one or two of the hangings, whilst the others stood sufficiently firm

The direct cohesion of larch timber, or the weight that a square inch would bear without being torn asunder, as stated in Tredgold's 'Elementary Principles of Carpentry,' edited by Peter Barlow, page 41,[1] is, according to Rondelet, 10,220 lbs.; and according to Bevan, 8,900 lbs.; the mean would be 9,560 lbs., which, multiplied by the sectional area in inches of the hanging-rods, $9'' \times 6'' = 54$

[1] Last edition (1870), published by Lockwood and Co.

inches, would give 516,240 lbs. as the weight that would tear each rod asunder; but it is further stated that the greatest constant load any piece should be allowed to sustain ought not to exceed one-fourth of its computed strength; therefore, each such hanging rod should not be loaded with more than 129,060 lbs. or about 57½ tons. The greatest weight of any shaft carried by the two rods was 67 tons, or 33½ tons to each rod, leaving a surplus strength sufficient to have carried fourteen tons more than it was loaded with.

If iron hangings had been used they would have been made of bar iron, of a thickness depending on the weight they would have to carry, which would vary with the different depths of the shafts. In Barlow's 'Treatise on the Strength of Materials,' the cohesive strength of good medium iron bars is assumed upon good data at 56,000 lbs., or 25 tons per square inch; and assuming one-third of that amount as the greatest constant load that should be applied, it would be 8·3 tons per square inch, and as four hanging-rods would be employed, each would have to bear one-fourth of the weight of the shaft, which in the case above quoted would be 16·75 tons. Now, an iron rod 1⅝-inch diameter contains 2·07 square inches; which, multiplied by 8·3 tons, gives the weight that such a rod would safely carry, namely, rather more than 17 tons: therefore the diameter of the bar employed to carry such a shaft should not be less than the dimensions above given.



The manner of applying such hanging-rods is shown in the annexed engraving. Figure 1 is a section of the shaft; and figure 2 a plan at the surface of the ground. Two balks of timber are placed parallel to each other across the shaft, and two other pieces are similarly placed across and at right angles to them, forming a square opening (A, fig. 2) to admit the traffic up and down the shaft. The upper end of each rod terminates in a strong well-made screw and passes through both

the balks and a stout iron plate, and is secured above by a nut; which screws and nuts should be carefully made, as the security of the whole chiefly depends upon them. Each of the balks should be well bedded on the ground, to give them a good bearing. The bottom of each rod passes also through a balk, two of which carry a strong curb, or square setting, upon which the brickwork of the shaft is constructed.

As it would not be practicable to have the hanging-rods in one piece where there is any great depth of shaft, they must be coupled at different lengths, as may be most convenient. Figures 3 and 4 show a method of forming these couplings—the one a face, and the other a side view—and as the proper length of these hanging-rods can be calculated in the first instance, they may be contracted for, and made ready for use immediately that they may be required.

Strong chains would be found a convenient form of hanging; and as they could be of an indefinite length, they would be applicable to any depth of shaft, and lowered as the shaft was extended downwards. Four chains would be required in each shaft, and applied in the same manner as the four iron rods are represented in use in the last figure.

There might be an advantage in the use of chains instead of stout bar iron for the above purpose, as they would be more manageable, and, in all probability, could be more readily appropriated afterwards to other purposes.

The following particulars may be useful, as connected with this subject:—

TABLE OF THE COHESIVE STRENGTH OF MATERIALS.

Or, the load in pounds that will tear asunder one square inch.

	lbs.
Iron—(good medium)	56,000
Oak—(English)	14,000
Beech	12,000
Ash	17,000
Elm	14,000
Mahogany	12,000
Walnut	8,000
Fir	12,000
Larch	9,560

In the erection of Menai Suspension-Bridge some trials were made of the strength of ropes used for the hoisting tackle to get up the main chains. They were as follows :—

	Tons per square inch.
1. A piece of $5\frac{3}{4}$ inches circumference ... broke with $6\frac{3}{4}$ tons . . . . . . =	2·56
2. A piece of $4\frac{1}{2}$ inches circumference, common laid ... broke with $4\frac{1}{10}$ tons . . . . =	2·54
3. A piece of $4\frac{1}{2}$ inches circumference, of fine yarn, slack laid ... broke with 6 tons . . . =	3·73

Taking the mean of No. 1 and 2 as a standard, it appears that *good rope will break with a strain of* 2·55 *tons per square inch of section.* But it ought not to be strained permanently with more than one-third of that—say three-fourths of a ton. For temporary purposes it might be loaded with half its breaking-strain, or $1\frac{1}{4}$ ton per square inch.

For finding the breaking-strain of ropes, the late Dr. Gregory gave the following rule :—

$$\frac{\text{The girth-square}}{5} = \text{the load in tons that will break the rope.}$$

Which appears to agree well with the experiments at the Menai Bridge; take for instance the first example, $5\frac{3}{4}$ squared=33·06, which divided by 5 =6·61 tons as the breaking-strain. The experiment gave a little more, namely, 6·75 tons.

CHAPTER VI.

SHAFT SINKING, CONCLUDED.

EXCAVATING AND SQUARE-TIMBERING THE LOWER PORTION OF THE SHAFTS.

THE under side of the shaft-sills, or of the timber settings carried by the hangings, was three feet from the intended level of the top of the brickwork of the arch; and upon their being made secure, the farther sinking of the shafts through the intended depth of the tunnel was proceeded with. Throughout this space, square settings of timber were placed at intervals of about six feet, and propped with rough timber from one to the other; the intervals were closely poled, or planked with three-inch deals. The cheapest materials that could be procured for this purpose were six-feet deal-ends. They were placed vertically behind the settings, which kept them tight against the earth behind, with a view to prevent any disturbance of its natural bed—this being the great object to be aimed at in all the timbering in mining operations: for so long as the earth can be kept undisturbed in situ, the minimum of pressure will be the result; but when once a movement takes place, unequal and uncertain weight is immediately thrown upon the timbers, which too often breaks them, causing a considerable loss of both timber and labour, and frequently attended with danger to the whole of that portion of the excavation, and to the lives of the workmen. It also frequently happens in argillaceous shales, or what the miners call 'blue ground,' that, upon exposure to the action of the atmosphere or moisture the earth will swell or expand. This was the case at Blechingley; where, occasionally, in the short interval of six feet between the square settings in the shaft, the three-inch planks were bulged or forced out in the middle,

which bulging would probably have gone on until the planks had broken, had this not been prevented by the insertion of an intermediate setting. As this happened but in a few instances, it would appear that six feet was a proper distance for the settings from each other; and the ground must be *very bad* to require them to be closer: at the same time, it would seldom be safe or prudent to place them much farther apart; for the saving would scarcely compensate any risk, as but little more than the labour in making the settings is lost, for being so soon released from the shafts the timber can be advantageously employed during the subsequent works, and the cost of the labour in making them amounts only to four shillings per setting.

The process of square-timbering, after what has been stated, will be fully understood by reference to Plates II. and III. In Plate II., figs. 1 and 2, and in Plate III., fig. 1, the square-timbering is shown complete. The section, fig. 1, Plate II., is taken across, or at right angles to the direction of the tunnel; and also shows by the dotted lines the position that the tunnel would occupy with respect to the shaft. The opening or position of the heading is also shown. Fig. 2 is a section at right angles to the former, or in the direction of the tunnel—showing the arrangement of the timbers in the shaft—and also a longitudinal section of the heading. Fig. 1, Plate III., is the same upon a larger scale; and fig. 4, Plate III., shows the upper part of the square-timbering immediately under the shaft-sills.

The method of framing or putting together the square settings is shown by figs. 5 and 6; A is the stretching-timber, which is placed across the shaft at right angles to the tunnel, as at figs. 1 and 2, Plate II.: B is the side timber placed in the direction of the tunnel, as in the figs. Plate II.; the stretcher, A, has a tenon at each end, to fix a corresponding mortice in the side timber, B; making, when the four pieces are put together, a clear square opening equal to the diameter of the shaft above (in this case, nine feet); but the side pieces were eighteen inches longer than the stretchers, consequently their ends projected nine inches beyond the square formed by the four timbers, and stood out like horns, as shown at D, figs. 5 and 6. The use of these horns was to form blocks at the back of the mortices and tenons, to

prevent the stretchers from slipping outwards, when the frame was in its place and the earth excavated from behind, during the subsequent excavations for the side-lengths of the tunnel. In like manner, the stretchers were prevented from being pressed inwards by chogs, C, figs. 5 and 6, which were spiked to the side pieces at one end of each stretcher after it was passed into its place; that part of the side piece being cut away, or sloped, to admit the tenon to pass into its mortice, which it otherwise would not do; as the excavation should not, in the first instance, be made so large as to admit of the side pieces being opened sufficiently wide apart to allow both tenons to be admitted into their mortices at the same time. Several ways have been adopted of framing the settings; but the one above described is probably the best, as affording the greatest security to the work.

When the ground has been excavated from beneath the shaft-sills to the proper depth, and the first setting put together, it must be placed exactly under the shaft, and square with the line of the tunnel; the earth may then be removed (or rather pared down, if it will admit of such a process), to allow the insertion of the three-inch poling-boards, or deal-ends, which should be driven close to each other, and bedded solid against the earth behind, by packing between the earth and the boards, if more excavation has been made than was necessary, or wherever a slip has taken place. The rough props, E E, &c., Plate II., can then be inserted and wedged tight at their ends; and, if necessary, spiked to the square timbers, to prevent their moving.

The work to the first square setting will now be completed; whereupon the excavation downwards may be continued through another space of six feet, by sinking in the middle of the shaft, and leaving a projecting bench of earth around, on which the first setting rests, in the same manner as explained and figured at page 58, when describing the shaft sinking. When this is done to the proper depth, the bench is cut away on two sides, for the insertion of the side pieces of a second setting, which must be placed perpendicularly under the setting (or settings) already fixed (they being temporarily propped to keep them from settling during this process). In like manner the earth is removed for the insertion of the stretching pieces on the two other sides of

the shaft. Some support may be obtained to the upper setting by temporary raking props, and by under-cutting the ground for placing the new setting, and subsequently removing the remainder of the earth to get in the props, E (Plate II.), and the poling boards.

In carrying on operations of this kind, so many new circumstances arise that require different modes of proceeding, even in sinking the same shaft, that it is only possible in a work like this to explain how it may be done, and how it has been done, and to state generally that some judgment is necessary to meet and overcome every difficulty as it arises; and, it may be added, watchfulness also, particularly where the ground is not homogeneous, as disasters in tunnel works are seldom rectified at a small cost, and may leave the works in a more or less precarious state.

The foregoing operation, or square-timbering, was intended to be carried no lower than the level of the top of the invert of the tunnel, which was also to be the level of the bottom of the heading. The setting marked F, Plate II., occupies this position; but in consequence of meeting with so much water during the shaft sinking, at both the tunnels, the square-timbering was carried down one setting, or six feet, below the said level, and thus formed a sump to collect the water, and for the barrels to dip and fill themselves, as they were raised and lowered by the machinery above to draw the water to the surface. The sump is shown in all the figures representing the square-timbering of the shafts.

It may be necessary to explain why in figs. 1 and 2, Plate II., the two settings B′ and C, immediately above the heading, are shown as being so much nearer together than the others. This arose from the use of six-feet deal ends as poling boards, which required that the said timbers should be placed six feet apart from centre to centre. Now, if this six-feet interval had been strictly kept to, the setting C would have been placed directly across the heading D, which, it is needless to add, could not be allowed; it was therefore considered better to place the two settings near to each other, and cut one set of polings shorter, rather than, by equally dividing the space above, to have to cut every set of polings to correspond thereto, which would have caused needless waste; or otherwise, the polings must have overlapped each

other behind, which would have been troublesome to do, and at the same time not so sound nor workmanlike a job.

In the above manner the work of shaft sinking was carried on, and satisfactorily completed at Blechingley Tunnel. The quantity of water in the shafts was various; in some it caused delay, in others none worth naming. The jack-rolls or windlasses were sufficient for raising both the earth and water, during which time the horse-gins were being made.

It had been the intention to have proceeded at Saltwood in the same manner as at Blechingley, but this was prevented by the great quantity of water, which rendered the ground a complete quicksand. The difficulties met with, and the method of overcoming them, will now be described.

The sinking of the shafts at Saltwood was commenced on June 11, 1842, and was carried on without intermission or difficulty until about July 13, when water began to appear, at a depth varying from sixty to sixty-five feet down. Small barrels were at first used to draw the water, alternately with a skip of earth; but, as the water increased, a second barrel was used at each shaft, and very soon the whole time of the men was taken up in drawing water only; it was therefore evident that the means then employed were inadequate to keep the water under, and enable the work to proceed. It was therefore resolved at once to fix up the horse-gins, and apply much larger water barrels than could be worked by manual labour. The gins were those made for, and used at, the works at Blechingley, and now required considerable repairs, which were done as fast as they arrived upon the ground from that place. All the pits, therefore, could not be got to work for some time, but were proceeded with one by one, as the gins could be prepared and fixed.

The large water barrels, with the manner of mounting them for use, is shown in the annexed engraving. A A are two centres, about which the barrel revolves when suspended by the large iron

bale. The ring B has a double motion, by turning in its socket, and the socket turning in the bale. Strong iron straps pass down the sides, and are crossed underneath the barrel, to strengthen it for carrying its weighty burthen; one of these straps is secured to the centre, A, and passes under the barrel to the opposite centre, whereby the whole weight is in a measure taken from the bottom of the barrel, and thrown upon the bale. The centres, A A, are placed below the centre of gravity of the barrel, which therefore will readily tip over, and empty its contents, when raised to the top of the shaft, where a trough is placed to receive and carry off the water. By this method the barrel need not be landed, but, as soon as it reaches the proper height, the banksman clips the top of the barrel with a hook, and releases the bolt, C, which slides upon the bale, and fits into a socket in the barrel to prevent its revolving until it is required to do so; and as soon as it is thus released, the barrel may be turned over towards the trough, and emptied, without any apparent exertion being required. When emptied, it

is placed upright, and the bolt, C, pressed into its place to keep it erect; and it is again lowered, to fill itself in the sump below. The ring, B, is secured to the end of the gin-rope by means of a shackle shown in the annexed cut; the rope thus yields and bends as soon as the barrel reaches the bottom, to allow it to roll over, and fill, without any risk of its becoming detached. The same shackles were used throughout the subsequent works; for when the barrels were not attached to them the large skips for raising the earth were suspended therefrom by means of a chain. The rope was 6¼ inches in circumference, and cost 50*s.* per cwt.

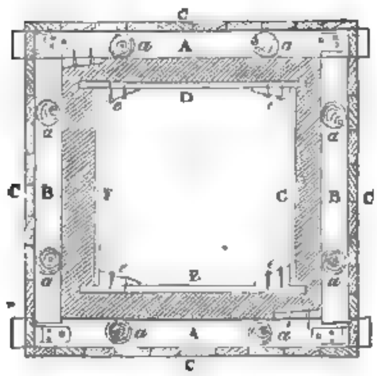
The dimensions of the water barrels are given in the engraving; the weight of each was 1 cwt. 2 qrs. 6 lbs.; the ironwork weighed 3 qrs. 20 lbs.; and when full of water the whole weighed 1,310 lbs.: and as they held 100 gallons, the weight of that quantity of water was 1,032 lbs. which gives 10·32 lbs. per gallon, which is about the usually estimated weight of a gallon of water. These determinations have been arrived at by weighing the parts and the whole, on an excellent weighing machine.

When the barrels had been got to work, and the shaft emptied, the sinking was resumed and carried on without intermission. The ground we were excavating was a dark-coloured sand and clay, nearly black (but which became lighter as it dried). The quantity of water it held made it of the consistency of soft mud, and as fast as we shovelled it into the skips the space from whence it was taken was almost instantly filled up again by fresh sand running from the back of the polings around the shaft. In this way we struggled with the work for some time, trying innumerable schemes to counteract the blowing or running of the sand, but to no purpose; for, in several instances, after a fortnight's work, we were less advanced than when we began. At length the following method suggested itself, after the repeated failure of other plans. This was called sumping; and its adoption was attended with success.

The plan was to drive the deal-ends, as if they had been sheet piles, behind the square settings, and remove the earth from the area of the shaft as they were driven. But, finding it impossible so to do, this operation was preceded by sinking a sump, about six feet square, at the middle of the bottom of the shaft, which was always kept as much lower than the ends of the said piles as was practicable, so that the sump sinking and pile driving were continued together. By this means the water was tended to the sump, and the earth above and around was left in a firmer state; for, it must be mentioned, the water followed us in our descent—or, in other words, the ground was drained to the level of our workings, and left comparatively dry, except in a few cases which were influenced by the upper springs. When this was done, the deal-ends being inserted behind the last square setting, were driven down by beetles (like piles behind a waling timber); at the same time the ground was shovelled from under them to admit of their descent. The earth was kept sufficiently dry for this purpose by drawing water from the sump as fast as the barrels could be worked, occasionally disengaging one of them, to hook on and send up a skip full of earth. As the pile driving proceeded, the sinking of the sump was continued, in order to keep the drainage as much as possible below the lower ends of the piles, and also that the barrels might dip and fill themselves; and when five or six feet were

thus gained, another square setting was inserted, as might be found to be necessary; and thus the work was continued to the bottom.

The making of the sump was the difficulty; and this was done as shown in the annexed engraving, which is a plan or section of the shaft at the level where the sumping commenced. A, A, are the side pieces, and B, B, the stretching pieces of the square timbers; C, C, C, C, are the upright polings or deal-ends at the back of the square timbers; *a*, *a*, &c. are sections of the upright props between the square setting, A, A, B, B, and the one above it; the shaded space represents the bottom of the shaft; and the space enclosed within the four sides, D, E, F, G, is the sump.



To make the sump, two planks, D, and E, were placed on their edges, parallel to each other, having triangular pieces, or chogs, *e*, *e*, *e*, *e*, securely spiked to them near their ends; between and at right angles to them two other planks, F and G, were placed, which were kept from being pressed inwards by the chogs, *e*, *e*, &c. When all four planks (or deal-ends) were thus placed, they formed a square frame nine inches deep. The area was then cleared of the sand and water, by two men, the one shovelling the sand into a skip, the other baling the water into the barrel, at the same time that two other men with beetles drove down the four planks; for it was impossible to clear the area within the planks without at the same time driving them lower, as the earth ran in so rapidly from behind as to fill the space immediately. When the planks were driven their whole depth (nine inches), four other planks were similarly placed upon them, and all secured together, so as to make a box twice the depth that a plank is wide, or eighteen inches. The sinking proceeded as before, and when they were down to the level of the bottom of the shaft, they formed a sump 18 inches deep. A third and a fourth set of planks were then placed above them, and lowered likewise, and so on till a sump several feet deep was attained, for the barrels to dip and draw off the water, while some progress was being made with driving

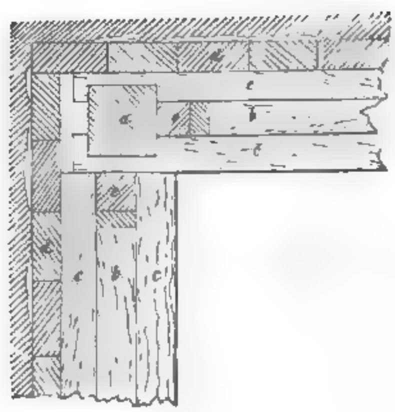
the polings or deal-ends behind the settings as before described. This, together with the sump-sinking, was then continued, as nearly as possible simultaneously, until the required depth of shaft was obtained. Behind every poling-board in the shaft, and wherever there was any space, a packing of straw was rammed tight, which had a good effect in preventing the live sand from running. The extensive use of this kind of packing was of the most essential service. The state of the work at this time, and throughout the subsequent driving of the heading, was so injurious to the health of the workmen, that about one-eighth of the whole number was under medical treatment for rheumatism, ague, or dysentery; which, however, proved fatal to but one.

NOTE TO CHAPTERS IV., V., VI.

By W. D. Haskoll, C.E.

Shafts.—Instead of the shafts being all constructed of brickwork, they may under more favourable conditions be entirely timbered from top to bottom, as it is often done, and constructed square on the plan.

In the angles are placed, *vertically*, longitudinal timbers about 6 feet long, and 9-inch scantling; these vertical pieces, *a*, are maintained by horizontal cross-pieces, *b*, of 9 by $4\frac{1}{2}$ inches, and by two similar pieces, *c*, notched fore and aft to the vertical timbers; the three last pieces are bolted together; behind comes thick planking, *d*, and the whole is tightened up by wedges, *e*. The annexed cut shows this timber work in plan; as the planking is introduced, care is taken to pack close behind it.



The vertical timbers, A, are scarfed at the end to admit of the next length being secured to them as the operations are carried on, and the scarfed pieces are bolted together. One moment's study will show that there is great strength in this system, and that it is very easily put together; careful packing behind the planking is an important element in its security.

CHAPTER VII.

DRIVING THE HEADINGS.

WHEN the shafts were completed, the heading or adit was commenced. The same dimensions were adopted, and the same settings used, both at Blechingley and Saltwood Tunnels. At the former place the work was done with comparatively but little trouble: the water that appeared passed into the sump at the bottom of the nearest shaft; and, there being no great quantity, the drawing of it to the surface delayed the general work but very little. At Saltwood it was otherwise: there the difficulties continued until the heading was completed through the hill, when the water ran off into the natural water-courses of the country—previously to which it all had to be drawn to the surface by horse power, as already described. It remains to state a few particulars as to the heading itself.

Figure 1 of the subjoined engraving shows a transverse section, and fig. 2 a longitudinal section of the heading.

FIG. 1.

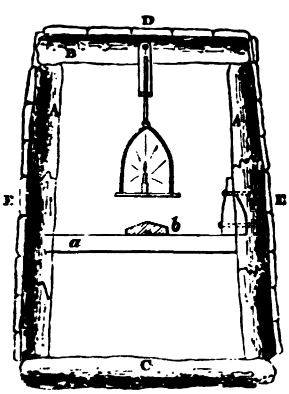
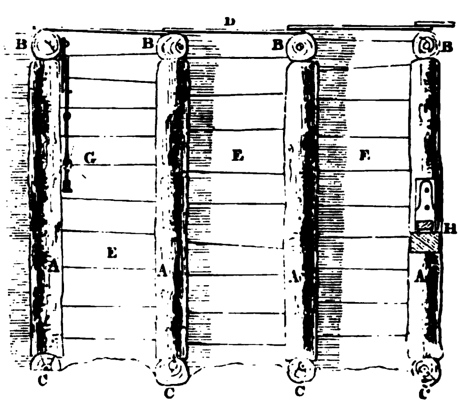


FIG. 2.



Similar sections may also be observed in some of the plates at the end of the work. The clear dimensions of the heading were—4 feet 8 inches high-

3 feet wide at the bottom, and 2 feet 7 inches at the top. Such were the dimensions of the frames or settings, which were made of round larch timber. The caps, B, and the sides, A A, were from five to six inches diameter, and the sills, C, four inches; the sides were tenoned into mortices in the caps and sills; they were placed at intervals of two or three feet apart, according to the character of the ground to be supported. The sides were closed by poling-boards, E, from $\frac{3}{4}$ to one inch thick; and the top, D, with poling not less than one inch in thickness. At Saltwood, the bottom under the sills was also poled quite close, and the whole packed with straw, to prevent the running of the sand, which but for the floor of poling-boards would have blown up from below, and filled the heading. In each of the figures the ranging-setting, and candle-holders, described at page 41, are shown.

The annexed engraving shows the manner of making the necessary excavation, and removing the earth from the heading to the shaft, which was done by means of a skip, upon wheels, which ran upon a temporary railway.

For this purpose, the rails consisted simply of strips of iron, one inch wide and $\frac{1}{8}$ inch thick, screwed down at the edges of long pieces of common fir scantling 4 inches by 3; which was spiked down to the sills of the square settings, and answered all the purposes required.

An inspection of the engravings at the end of the work may lead to the remark that the headings were driven at the level of the top of the invert; and a question might arise as to the reason for taking that level, in preference to others. The object in so doing was to keep the drainage of the works at all times free; namely, upon the same level in the finished portions of the work as in the headings at the unfinished parts; and the only interruption thereto arose when the ground was excavated for a new length of brickwork;

in which case, the water was carried across the twelve-feet space in a wooden shoot, and what little leaked into the excavation was baled out by the bricklayers' labourers. If the heading had been placed at a lower level, the works would have been always under water to the level of the top of the invert, as soon as any portion of it was completed, and a continued annoyance and expense would have been the result, independently of the greater risk of having unsound work from the effects of the water. Had the heading been driven *altogether below* the invert and a culvert constructed before the tunnel works had been begun, a great additional outlay would have been the consequence; and the culvert thus made under ground, in so confined a space, would probably have been badly done, and there would have been an unsound foundation for the invert of the tunnel: moreover none of the advantages of the heading for the purposes of ventilation, ranging the lines, and levelling, would have been obtained. On the other hand, if the heading had been driven at the level of the *top* of the tunnel, all its advantages in draining the works would have been lost; the ranging by the method of lines along the heading, for setting the ground-moulds, as explained in Chapter III. would have been less conveniently done, and with greater uncertainty as to its accuracy. If, therefore, there is not a certainty of the ground being quite dry (which is rarely to be expected), such a situation for a heading appears to have but few advantages to recommend it.

HORSE POWER.

During the progress of water-drawing there appeared an opportunity of obtaining some results as to the power of horses. Having found it desirable to ascertain the amount of labour performed at the various shafts, in order to determine from day to day, not only whether the difficulties were increasing or diminishing, but also correctly to fix the duration of horse-labour at each working—otherwise there would have been opportunities of deception and misrepresentation—all the horses being hired (at the price of 7*s*. per diem). Besides which, it appeared that, by keeping a daily register of the work

actually performed by the horses in each given time, there would be collected a quantity of facts relative to horse power that might prove useful in assigning an approximate value to that uncertain coefficient. The register —which extended from August 25 to October 24—was kept by my friend and assistant, Mr. P. N. Brockedon, in the manner shown in the following table, which is a copy of the register of work done at nine shafts, on September 17, 1842; and is sufficiently explanatory of the mode adopted in arriving at the results.

SALTWOOD TUNNEL.—WORK DONE BY THE HORSES IN THE GINS,

For the twenty-four hours ending 6 A.M. September 17, 1842.

No. of Shaft	Number raised during 24 hours, of			Average Number per hour, of			Weight in pounds raised per hour, of			Total Number of Pounds raised the full height.		Height raised, in feet.	Number of Pounds raised One Foot High per Minute.		Time that each Horse worked, in Hours.
	Water Barrels.	Large Skips.	Small Skips.	Water Barrels.	Large Skips.	Small Skips.	Water Barrels, each 1,310 lbs.	Large Skips, each 1,050 lbs.	Small Skips, each 500 lbs.	Per Hour.	Per Minute.		By two Horses.	By each Horse.	
1, 2, 3	Not in operation.	.	..	...	..	..	.	..	...	..	.	...	...	...	...
4	398	5	100	16·6	0·2	4·2	21,746	210	2,100	24,056	400·9	95	38,086	19,043	4½
5	649	73	..	27·0	3·0	...	35,370	3,150	..	38,520	642·0	110	70,620	35,310	3
6	725	47	...	30·2	2·0	...	39,562	2,100	...	41,662	694·4	108	74,995	37,498	3
7	647	53	..	27·0	2·2	...	35,370	2,310	...	37,680	628·0	107	67,196	33,598	3
8	693	58	..	28·9	2·4	...	37,859	2,520	...	40,379	673·0	103	69,319	34,660	3
9	446	92	...	18·6	3·8	...	24,366	3,990	...	28,356	472·6	101	47,733	23,866	6
10	605	55	..	25·2	2·3	...	33,012	2,415	...	35,427	590·4	100	59,040	20,505	6
11	420	38	.	17·5	1·6	...	22,925	1,680	...	24,605	410·1	100	41,010	20,505	6
	333	43	...	13·9	1·8	...	18,209	1,890	...	20,099	335·0	95	31,825	15,913	6

Upon the completion of the water-drawing, namely, when the shafts and heading were finished, the following mean results were obtained as the power of horses working a given number of hours per diem :—

Horses working three hours per diem, mean of 112 results, = 32,943 lbs. raised one foot high in a minute.

Horses working four hours per diem, mean of 4 results, = 37,151 lbs. raised one foot high in a minute.

Horses working four-and-half hours per diem, mean of 12 results, = 27,056 lbs. raised one foot high in a minute

Horses working six hours per diem, mean of 212 results, = 24,360 lbs. raised one foot high in a minute.

Horses working eight hours per diem, mean of 4 results, = 23,412 lbs. raised one foot high in a minute.

In the determination of the value of horse power from the above results, the three and six-hour experiments alone should be adopted. The other results were more or less objectionable, from a variety of causes over which there could be no control, and are therefore of less practical value.

The following table of estimates of horse power will afford some means of comparison with the above results.

Name.	Pounds raised 1 foot high in a minute.	Hours of Work.	Authority.
Boulton and Watt	33,000	8	Robison's Mech. Phil., vol. ii. p. 145.
Tredgold	27,000	8	Tredgold on Railroads, p. 69.
Desagulier	44,000	8	Dr. Gregory's Mathematics for Practical Men, p. 183.
Ditto	27,500	Not stated.	
Sauveur	34,020	8	
Moore, for Society of Arts	21,120	Not stated.	
Smeaton	22,000	Not stated.	

These are higher results than were given by the average of the Saltwood experiments, and more nearly accord with the maximum there obtained, which was as follows.

Horses working 3 hours	maximum =	47,895 lbs.
Horses working 4 hours		39,694 „
Horses working $4\frac{1}{2}$ hours		35,300 „
Horses working 6 hours		36,819 „
Horses working 8 hours		36,630 „

But with such high results, or anything approaching thereto, the horses sank under the excessive fatigue, and eleven of them died. Nearly one hundred horses were employed, which were supplied by Mr. Richard Lewis, of Folkestone. They were of good quality; their average height was 15 hands $\frac{1}{4}$ inch, and their weight about $10\frac{1}{2}$ cwts., and they cost from 20*l.* to 40*l.* each. They had as much corn as they could eat, and were well attended to.

The total quantity of work done by the horses, and its cost, was as under :—

Registered quantity of water drawn 104 feet, the average height, 28,220,800 gallons	=128,505 tons.
Ditto, ditto, earth 3,500 yards ... 1 ton 6 cwt. per yard	= 4,550 „
Total weight drawn to the surface . . .	133,055 tons.
Total cost of horse labour, including a boy to drive each horse	£1,585 15*s.* 3*d.*
Or 2·85 pence per ton, the average height of 104 feet.	

A paper upon the subject of horse power, containing the full particulars of the Saltwood experiments, by the author of this work, was read before the Institution of Civil Engineers, on the evening of March 14, 1843.

CHAPTER VIII.

CONSTRUCTION OF THE TUNNELS.

THE SIDE LENGTHS—EXCAVATION AND TIMBERING.

THE excavations for the tunnels at Blechingley and Saltwood were carried on in a similar manner. One description of the general process will therefore suffice; with such occasional particulars of any peculiarity in the circumstances of either as may have arisen in the course of those works.

On the right-hand half of fig. 3, Plate I., are shown a number of horizontal lines drawn at intervals of 1 foot from the exterior crown of the arch downwards, and the length on each line (in feet and inches) from the centre vertical line to the exterior of the brickwork throughout the whole depth of the work is given. Also from the same point (the external crown of the arch) oblique lines are drawn to the extremities of the said horizontal lines, and the length of such oblique lines are given at the outside of the figure on the right hand. By these two sets of lines it will at once be seen that the figure of the tunnel could be laid down independent of the radii given on the left of the figures; their application was, however, to guide the miners in excavating the earth to the correct dimensions; for, as they commenced at the top and worked downwards, they had this guide in taking out sufficient earth to admit the insertion of the tunnel without removing more than was necessary. A plumb-line was hung from the roof in the centre of the tunnel, and upon this line a knot was tied at every 12 inches of its length. A tape, to represent the corresponding line on the working section above spoken of, was stretched horizontally from any one knot to the extent of the excavation, at right angles to the line of tunnel, which determined whether or not sufficient earth had been removed: thus at 8 feet down it required a space of 12 feet 2 inches to be removed on

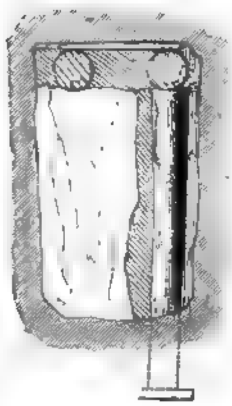
each side of the line, and as a check, another distance to the same point was occasionally measured from the intended crown of the arch which is marked outside of the curve in the figure; at 8 feet down, this oblique distance was 14 feet 6¾ inches.

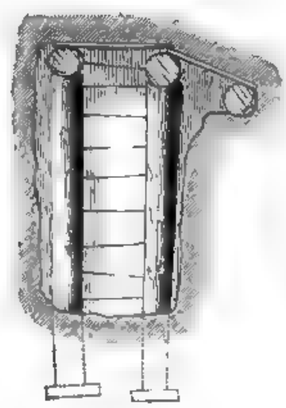
The dimensions furnished to the miners were those of the outside of the intended brickwork; they had, therefore, to excavate still further to receive the timbers that were required to support the earth. These extra dimensions were supplied by themselves, at the time; dependent upon the substance of the timbers necessary, together with the requisite allowance for subsidence, as the character of the ground might have pointed out. This extra space for the timber, &c., beyond that required for the brickwork of the tunnel, will be readily understood upon reference to such plates, at the end of the volume, as contain transverse sections of the finished tunnel; of which there are several examples given.

The work was commenced by removing some of the polings, or deal ends, from behind the two top settings of the square-timbering of the shafts; and driving a narrow heading about 12 feet long, at the top, and in the middle of the intended tunnel. Where the ground is good, and will stand without much timbering, the top heading (as it is usually called) may have rather large dimensions; but must be limited in this respect where the ground is loose or treacherous. The headings at Blechingley and Saltwood were sufficiently high for a man to stand upright in, and about 3 feet in width. In some of the headings at the former tunnel no poling boards were required in so small an excavation, but at the latter place they were in all cases necessary. No regular system of framing was used, but pieces of poling boards were put up and secured in the best and most convenient manner, wherever the earth showed symptoms of falling in, but so arranged (where it was possible) as to form part of the subsequent roof of the excavation. The top of this heading was so much above the intended soffit of the arch of the tunnel as to admit the proposed thickness of the brickwork, and that of the crown bars, packing, and poling boards, together with the allowance of several inches for the settlement of the timber which is certain to take place when more of the excavation is made, and before the brickwork can

be inserted to take the weight and relieve the bars of their burthen. This allowance should never be omitted, for when such settlement takes place, and no room has been previously left for its occurrence, a part or the whole of the crown bars in sinking occupy the position of the intended brickwork; and therefore, in order to insert a tunnel of the required dimensions, the bars and poling boards must be raised to their proper level; which is only to be done piecemeal, by removing the earth over each bar, and then raising them one at a time: this involves considerable labour and care, and no trifling expense.

When the heading is driven, it is widened at the top along one side, to form, as it were, a shelf upon which a crown bar may be laid lengthways. When this is done, the centre crown bar is placed along the top heading, and supported against the roof by an upright prop at the remote end, and by resting it on the square timbering of the shaft at the near end; poling boards are then arranged above the two bars to carry the earth. This is shown in the annexed section of the top heading. A similar excavation or shelf is next made on the other side of the centre crown bar and a third bar placed thereon, and poling boards inserted above, as in the first instance; a narrow slip of ground is next removed from under the remote ends of the two side crown bars, to the bottom of the heading; and rough props inserted to support them in the same manner that the centre crown bar is supported; their other ends being in like manner supported by the square timbers of the shaft. The earth may next be removed from under the two side bars, which leaves the heading much wider than before.

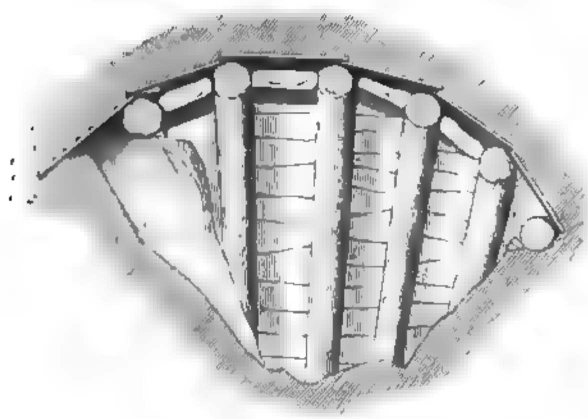




Sometimes, when the top heading is wide enough, two crown bars are inserted and poled above, and the insertion of the side bars (by excavating a shelf to the right and left, as before described) is then proceeded with in the manner shown in the annexed engraving. The bars are kept at the proper distance apart by

inserting five or six struts between every two bars, as shown in the next engraving, also at s s, &c. in fig. 2, Plate III., and in each plate that contains a transverse section of the timbering of the tunnel. The temporary props, at the remote end of the bars, rest upon flat foot-blocks, to prevent the superincumbent weight pressing them down. The foot-blocks are either placed at the bottom of the heading, or the ground is dug up to admit of their base standing upon the intended level of the under-side of the top sill. In either case, they are placed far enough outwards to admit thereafter of the sill being placed in front of them. The dotted portion of the props and foot-blocks in the above cuts, shows the end of the props so placed below the bottom or floor of the heading; however, it is not always that the ground will allow of this being done in the first instance. The perpendicular face of the work is secured from falling in by the insertion of poling-boards across it, at the back of the props as shown in the last figure.

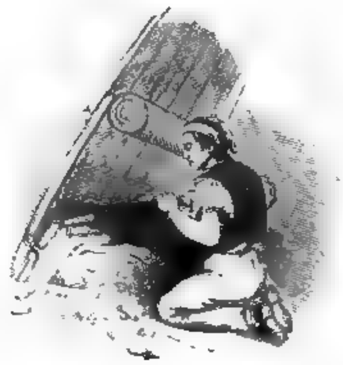
In the manner above described, bar after bar is inserted to the right and left of the top heading; propped and strutted from the ground and from each other; and the poling-boards inserted both in the roof and against the face of the excavation, the bars being so arranged as to follow nearly the intended figure of the tunnel; or, rather, such an arrangement is preserved as will be best suited for the subsequent insertion of the brickwork, as will be hereafter explained.



The annexed engraving shows a section of the work in this stage of progress, which is technically called 'getting in the top.'

The manner of forming the roof of the excavation by poling-boards over-lapping each other behind the bars, is shown in the engraving on the next page; where a miner is represented as preparing for the insertion of another bar.

From what has above been stated, together with an examination and comparison of the engravings, it may be hoped that the matter has been sufficiently explained to require no further observations.



It has been stated above that the near end of the crown bars is at first temporarily supported or propped from the square timbers in the shafts; it must, however, be observed that, by so doing, a great weight is thrown upon the square timbers in addition to that of the brickwork of the shaft, which is all that it is designed to carry, and in which it is materially assisted by the hanging-rods or shaft-sills described in the preceding chapters; and, for this reason, the square timbers should be as speedily as possible relieved from the weight of the bars, and whatever pressure of earth they may be sustaining. This is finally done, when the top sill next the shaft is inserted in its place, by propping every bar therefrom. When the ground is good, there is no danger in temporarily supporting the near ends of the crown bars from the square timbers; but where it is soft or yielding, it is unsafe thus to load them; for, under such circumstances, the ground, instead of steadying the square timbers, is liable to give under the pressure; and when once the square timbers get out of the perpendicular they would require no great additional weight to force them in, and the yielding or soft ground which would thus lead to the accident would follow from behind the shaft, and in all probability bring the shaft down with it.

This was precisely the kind of accident that occurred, in one instance, upon first starting the Saltwood Tunnel. The sand had become extremely porous, and consequently yielding, by the draining of the water therefrom, to a great extent, as described in the preceding chapters. Not only was the earth porous, by the absence of the water, but large spaces (in some instances, complete caverns) had been formed behind and around the square timbers, by the sand having run into the shaft, and been drawn to the surface with the water. Under such circumstances, it was no wonder that half the

weight of the first side lengths being thrown upon the square timbers (in consequence of the bars having been propped therefrom), should have caused their downfall and the destruction of the shaft—the porous nature of the ground and the existence of the caverns being unknown at the time.

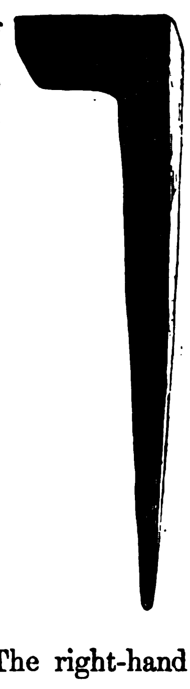
The necessity of relieving the square timbers from the weight of the bars as speedily as possible cannot be too strongly impressed upon the reader; and such relief may be obtained to a great extent, if not wholly, by temporarily propping, upon planks of timber laid across the then floor of the excavation, near the shaft, or at the middle of the length, or both, as circumstances or the progress of the work will admit of, during the removal of the earth for, and the insertion of the shaft top sill, D, fig. 1, Plate III., which should be got into its place as speedily as possible.

A completely arched roof of timber is constructed, in the manner now described, and shown in the upper portion of fig. 2, Plate III., above the sill, A A; but, as at present explained, it is left supported at the face by props resting upon the earth, at the level of the under side of the top sills, each prop standing upon a broad base in the form of a foot-block, to prevent its being pressed into the ground, which would cause the roof to give way: therefore, as soon as the whole of the bars to the intended level of the sills are inserted, or even sooner, if possible, the sills themselves should be got into their places. The bars are longer than the first length of brickwork is intended to be; so that, at the face of the excavation, the top sill, A, may be placed in front of the advanced props, and as soon as the sill is placed another prop may be fixed from the sill to support each bar. These props, therefore, stand in front of the advanced props, which are hid in the section, fig. 2, Plate III., but are shown in the longitudinal section, fig. 1, Plate III.—where A is the top face sill, F the crown bar, G the advanced props, corresponding to those shown in the cuts at pages 93 and 94, and A the permanent prop. In a similar manner the sill, D, next the shaft, is inserted, and the bars propped therefrom, as I, fig. 1.

The sills (which are called miners' sills, to distinguish them from the centre sills, to be hereafter spoken of) are made of whole balk, 12 or 14 inches square, according to the nature of the ground; or, in other words,

the scantling for the timber of the sills must depend upon the weight or pressure they are intended to sustain or resist. Their length was about 36 feet, in two pieces, scarfed together in their middles, and secured with iron plates, bolts, and glands, as shown at fig. 2, Plate III. where A A is the top sill, and C C the lower sill. The weight of the iron work for the scarfing of each sill was 1 cwt. 2 qrs. 14 lbs.; and the price paid for labour, including sawing, was 4*s.* 6*d.* per scarf. Each scarf was 5 feet in length.

When the sills are well bedded in their places, they should be set level and the props from them to the bars above be driven or wedged tight, and secured from the chance of disturbance by driving a peculiarly formed spike, called a *brob*, of wrought iron (as figured, half the real size, in the margin) around the ends of the props into the bars and the sills. The brobs are shown in their places in figs. 1 and 2, Plate III.; and in most of the engravings where their use is required. The tops will now have been completely got in, and the whole weight of the bars, with that of the earth pressing on them, will be supported by the sills, which by their greater length present a large base, and no settlement can take place in any one bar or prop but must equally affect the whole, unless the sills should have been unsoundly bedded in the first instance, or subsequently unequally propped when the earth is removed from below, in the further progress of the work. At this stage of the work the stretchers M M, Plate III. should be inserted, to prevent the sills from being pressed inwards by the earth against the face of the work. The right-hand portion of fig. 1, Plate III. shows the excavation with its timbering ready for the reception of the brickwork as it appears longitudinally or in the direction of the tunnel; fig. 2 shows the appearance of the same timbering, as seen at right angles to the former; and by a comparison of the two figures the corresponding parts in each may readily be distinguished.



When the top sills are in their places, and the roof finished as above described, the excavation downwards, for the insertion of a second sill, may be proceeded with. So much care is not required in this part of the work

as in getting in the tops. A narrow passage should first be made along the middle of the length, corresponding with the top heading before described, and temporary raking props, K K, fig. 1, resting upon foot-blocks, should be placed under the sills to carry them till they can be propped from the next lower sill, after its insertion. The temporary, or, more properly speaking, advanced props, K K, rake outwards, to admit of the sill being placed and adjusted vertically under and in all ways parallel to the one above; whereby when the final props, P P, are inserted between them, the lower sill will receive its weight in a manner best calculated to sustain it. For the insertion of each raking prop, a narrow space is first excavated from under the sill, which leaves between the places so excavated a pillar (or pilaster) of earth, that supports the sill until some of the raking props, K K, are secured in their places. The remaining earth may then gradually be removed, and other raking props inserted, until sufficient stability is secured to the sill above.

What has now been stated relates only to the face sill. The mode of proceeding for the corresponding sill, E (Plate III. fig. 1), adjoining the square timbers of the shaft, is somewhat different, inasmuch as raking props cannot be in this case applied, excepting near the extremities, on account of the open space forming the shaft. The support required for carrying the upper sills and the tops may be obtained by temporary props raking inwards, placed where they are not in the way of the insertion of the sills; or, if so, they must then be shifted to another place. And where there is confidence in the stability of the square timbering of the shaft, a portion of the weight might be temporarily carried by propping the sill from them, as shown at L, fig. 1, Plate III.; but this mode of proceeding is best avoided, unless the circumstances of the case compel the miner to have recourse thereto, for reasons before explained.

As soon as the upper sills are temporarily secured, and the earth cleared away from under them to the proper level, the second sills may be inserted and the upright or permanent props P′ P′ be fixed between the bottom and top sills. These props should be set perpendicularly and vertically under the upper ones, which cannot be done unless the sills are truly under each other. When this set of props is inserted and properly secured with brobs, the remainder of the earth in the length down to the level of the second sill

may be removed; and as the sides are excavated to the required form and dimensions of the tunnel, by hanging a centre-line, as before described, additional bars, poling-boards and props may be inserted to support the earth. Stretchers also, from sill to sill, in the direction of the tunnel, as shown at M M, &c. Plate III., must be inserted to prevent the sills from collapsing by the pressure of the earth on either face of the excavation.

In all cases, except where the ground is good, the faces of the excavation, as well as the roof, should be poled behind the advanced or raking props more or less close, according to the character of the earth; and where it is running sand they should be well packed behind and at the joints with straw, which at Saltwood proved a valuable auxiliary.

The section, fig. 2, Plate III. shows the arrangement of all the timbers described between the top sill, A A, and the bottom sill, C C. This arrangement is precisely that followed at Blechingley; but at Saltwood a third sill was used, which was placed immediately over the top of the heading. The second sill was placed midway between the upper and the lower one—see Plate VIII.—which represents a section through the middle of the side lengths at Saltwood, and shows the three sills and the mode of timbering there adopted; and which, in all probability, would be suitable for the heaviest ground that occurs in ordinary practice. Such a peculiar situation as that of the Thames Tunnel of course forms an exception; so extraordinary a work required means to be employed that were, in like manner, out of the common way, and could only have been supplied by such a master-mind as his who executed it—Sir M. I. Brunel. When a third sill is used, the mode of excavating between it and the one above is precisely the same as that just described.

The following engraving shows the excavation going forward for the second sill; but it is likewise intended to represent the work in a more advanced state, namely, the construction of the *leading* lengths; and, as such, it will be again referred to in a subsequent chapter. But, although it does not represent the work quite as it would proceed for a *side* length, yet, by examining and comparing it with what has been stated, some help may be obtained in understanding the present descriptions.

After all the sills required for each length are inserted, the excavating

and timbering of the lower portion of the length is very simple. A gullet, or narrow passage, should be excavated down to the level of the skewback of the inverted arch through the length, similar to the narrow passage, described at page 98, and which is there represented as corresponding with the top heading previously described. The gullet must then be widened out to the full width of the tunnel; and as the earth is removed from the vicinity of the bottom sills, care must be taken to prop them in the most convenient

manner that the state of the works will admit of, whilst the earth is gradually being removed from under them to admit of upright props being there placed to carry the weight. But temporary propping must first be resorted to (in this, as in almost every instance of tunnelling operations), because the permanent (or final) props cannot be got into their places until the ground has been excavated beneath the level of the skewback, in a proper figure for the reception of the inverted arch; which must be the next and last opera-

tion of the miner, previous to the bricklayers entering upon the constructive part of the business.

In Plate III. and in others of the engravings at the end of the work, the timbering of the lower portion of the side lengths is shown; and, after what has now been described, together with an inspection and comparison of the figures in the several engravings, no difficulty can arise in comprehending the whole of it.

Considerable care is necessary in shaping the ground for the inverted arch; for it is as important that it be constructed of as true a figure as the arch overhead is required to be, and which the bricklayers cannot do in a sound and satisfactory manner unless the ground is correctly shaped for its reception.

In the figures at Plate III. and some others, the timbering on the face is shown as if continued down to the bottom—at least to the skewback level. This was in all cases necessary at Saltwood, but only in some instances at Blechingley; for there the ground was occasionally so good as to stand, for the short time that it was required to do, without any timber below the level to the bottom sill, as shown in Plate VI.

When the excavation of the side length is complete for the reception of the brickwork, it presents the appearances shown in section at fig. 2, and the right side of the shaft, at fig. 1, Plate III.

CHAPTER IX.

CONSTRUCTION OF THE TUNNELS, CONTINUED.

THE SIDE LENGTHS—BRICKWORK.

By reference to the transverse sections, fig. 3, Plate I. it will be seen that the brickwork of the side and shaft lengths was thicker than in the leading work. This is the usual practice, because these lengths have always more work to do, being liable to be tried with greater strains than the other portions, particularly the side lengths, when first constructed, for they then remain a long time before they receive any assistance from the adjoining work.

The first thing to be done as soon as the excavation is completed is to set a ground mould at each end of the length, to guide the bricklayers in constructing the inverted arch to the required form and dimension; D, fig. 2, Plate III. shows a ground mould as set in its place ready for the bricklayers to work. It forms part of what is called a *leading frame*, of which E E are the side walls, or, rather, the moulds to which the side walls are constructed. F and G are stretchers, or cross bars, which connect the parts of the frame together, and keep them at their proper distance apart; and thus altogether these several parts form the leading frame, and, placed upright against the timbered face of the excavation, as shown at O O, fig. 1, Plate III. guides the bricklayers in carrying on the work.

The inverted arch is built in front of or against the ground mould D, the two ends of which are formed as at L, and constitute the skewback, from which the side walls of the tunnel spring. The points where the curve of each side wall meets that of the invert mould, as at *a*, is the part alluded to in Chapter III. page 43, &c. as the *invert skewback*, when describing the

requisite levelling operations. At fig. 2, Plate III. and at Plate VIII. (which represent the side lengths of the two tunnels under consideration), it will be observed that the ground moulds are not imbedded on the ground, but elevated 9 inches above it, and propped in that position in several places, by bricks laid flatways on each other and wedged up to the proper level; this was done for all the side lengths at both tunnels, and also for the first leading lengths at Saltwood.

The ground moulds were made of Dantzic timber, 3 inches thick, and in two parts, scarfed and united in the middle by iron plates and bolts, as shown at *b*, fig. 2, Plate III. It would have been better to have made these in one piece, but in that form they could not have been got down the shafts into their places—their length being too great to admit of their turning the angle from the shaft into the excavation, through the confined spaces between the timbers; but where shafts of a larger diameter are used, such ground moulds may then be got down whole. The stretcher, G, was in one piece, 5 inches by 3 inches, and was made to drop into a socket at each end, formed by iron plates at the skewback, as will be shown more fully in the engraving on the 108th page. I I are two upright pieces, or plumb rules, fitted between the stretcher, G, and the invert mould, D, by mortices and tenons; their use was to give stability to that part of the frame. By their plumb lines the ground mould was set upright, and would, if all its parts had been made very correctly, have determined when the mould was truly level; but it was never depended on for that purpose, as the spirit level, when placed in the length, was both a correct and ready means of so doing. Upon the stretcher, G, and upon the ground mould, the centre line was marked with a saw kirf, to enable it to be placed centrally under the ranging line, when stretched along the heading for this purpose, as explained at page 42. In each side length there was of necessity two leading frames used for the starting of the work; after which one only was required in each length, as the brickwork already constructed answered the purpose of the other. On the right hand side of the shaft, fig. 1, an end view, or section, of the leading frames is shown, at O O, as set against the back and front of the excavation ready for the bricklayers.

The side walls of the tunnel were built outside of the moulds, E E, or between the moulds and the earth; the intervening timber (the bars, &c.) shown in the engraving, fig. 2, were removed as the brickwork was advanced upwards.

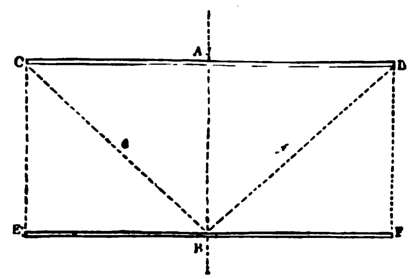
The ground moulds required to be carefully set and secured in position, so that the centre line marked thereon might coincide with the intended centre of the tunnel, and that they might also be at their proper relative level. For this purpose the level of the skewback of the invert was adopted in all cases, as before stated. The method of setting these leading frames or ground moulds was as follows:—

After being lowered and put together, they were approximately placed against each face of the excavation; the hanging rods were then suspended from above, to obtain the levels, as described in Chapter III. page 45, &c.; and the ranging line was stretched along the heading on each side of the shaft (being passed through two or more holes in the ranging blocks, *b*, described at page 42), representing the intended central line of the tunnel, with which the centre mark of each leading frame should coincide. A spirit level was then set up in a convenient part of the excavation, to determine the levels of the skewbacks by the hanging rods, the bottoms of which were graduated, as at A, in the engraving, page 46, similarly to a levelling staff. If this had not been done, a staff must have been held alongside the rod, which would not have been so satisfactory an operation. To determine the levels of the ground moulds, a staff, divided like the hanging rods, was held thereon, and by directing the level to each, alternately, it could be ascertained if the mould was too high or too low; in either case it was adjusted to the proper level by means of wedges, and, if necessary, more earth was removed from under it. A lighted candle held near the staff, or rod, was sufficient to render the graduations distinctly visible.

In the above manner the ground moulds were set exactly in line and at the proper level; but in addition thereto it was necessary that the plane or face of the leading frame should be perpendicular and be at right angles to the centre line; the former was regulated by the plumb lines, I I, fig. 2, Plate III. and the latter was determined as follows:—A nail was driven into some

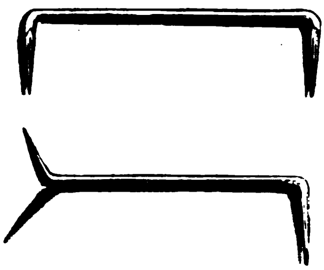
timber at the shaft end of the length, exactly in the centre line, and from thence was measured the distances to the skewback points at each end of the mould. If the two measurements were equal, the mould would be correctly square; but if the distance of the central nail to one end of the mould was greater than the distance to the other end, it was a proof that the mould was not at right angles to the centre line; and therefore one end was moved inwards, or the other end outwards, or both, until the distance from the said central nail to any assumed point on the mould (as the edge of the skewback) was the same.

This explanation will be better understood by reference to the annexed plan. Let A B represent the centre line of the tunnel; C D one of the ground moulds; B a nail (as above described) in the centre line. From this nail the distance B D must be equal to the distance B C, in order that the mould, C D, be at right angles to the line A B; if it be not so, the mould must be so moved until it answers these conditions, in order that it may be correct.



When one of the moulds is set square, the other may be brought parallel thereto by simply moving it, until its two ends be equidistant from the two ends of the one already fixed. Thus, in the engraving, if E F represent the second ground mould, it must be moved until its centre coincides with the centre line, A B, and the distances of its ends, E and F, are equidistant from the ends, C and D, of the other mould respectively. When both the ground moulds are set *straight, level, and square,* they may be secured in their places with respect to each other, and prevented from collapsing or expanding by means of narrow pieces of board nailed from one to the other near to their ends; and also, with respect to their position in the tunnel, by a kind of holdfast, called a dog (shown in the annexed cut), driven into the mould and into the adjoining timbers, wherever it may be convenient. This kind of holdfast is very useful in such like operations. They consist of a piece of round iron, with pointed ends turned up at right angles to their length, and in some of

them at right angles to each other; these points, or spurs, can then be driven into the timber in opposite directions. A number of them, of various sizes and degrees of strength, should always be at hand, to be applied as circumstances may require.



During the early proceedings at Blechingley, the first ground moulds were ranged centrally by suspending two lines down each shaft, from the ranging frame described at page 36, and by moving the mould until the two lines were seen to cut its centre, where a lighted candle was placed. This was but an uncertain and unsatisfactory mode of proceeding, even when all circumstances were favourable; but when, from thick weather, the lines could not be tested above by the transit; or, if tested, could not be depended upon by reason of high winds forcing them out of the perpendicular, it became so doubtful that it would have been imprudent to adjust by them at all. Consequently it occasionally happened that a delay took place in setting the moulds, and thus a large excavation was left for some time to the strength of the timbers only to carry the earth; which, in unfavourable ground, to say the least of it, was hazardous. This kind of delay led to the fixing of posts securely in the invert, and adjusting to each of them an iron cap, with a central hole through which to pass a line to another central point, fixed at a distance in the heading, whereby the line was passed over each ground mould that would require adjusting; and, having thus obtained central as well as level points below, the work could be carried on without delay or dependence on the contingencies of the weather; and led, at Saltwood, to the contrivance and adoption, in the first instance, of the ranging spikes described and figured at page 39.

It may not be thought unnecessary to recapitulate the points to be attended to in setting the ground moulds.

1. The furthest mould from the shaft should be fixed.
2. It must be upright as determined by the plumb lines attached to it.

3. Its centre must coincide with the centre line of the tunnel, as determined by the ranging lines.
4. Each end must be set to the same level; which level is to be derived from bench marks already established below, or from the hanging rods suspended in the shaft for that purpose. In transferring the levels to the skewback, due allowance must be made for the rise or fall of the tunnel (if any) according to the gradient.
5. It must be at right angles to the line of tunnel, as determined by measuring from a distant central nail to each end of the mould.
6. In the side lengths, the back, or second mould, must be set parallel to the first, by placing it so that its ends may be equidistant from the ends of the mould first set.

When the two ground moulds are set, the miners should trim the ground correctly to receive the brickwork of the inverted arch. This they can do by following the line of the under side of the moulds.

Upon the face of the ground moulds and side walls every course of bricks was distinctly marked (or cut in), to which the bricklayers were required to work. These lines were determined by the size of the bricks to be used, and, unless rigidly adhered to, there would have been great irregularity in the courses at the junction of length upon length, which would have been bad in appearance and deficient in strength.

The invert was constructed with concentric half-brick rings, bonded, in each case where the joints became flush, excepting about 6 feet on each side from the springing at the angle of the skewback, which was constructed in English bond. At Blechingley the bricks for the skewback were made of a suitable shape, but at Saltwood the common bricks were cut for that purpose. In some instances stone has been employed, whereby the skewback is made in one piece for lengths of about 3 feet; but this method was considered too expensive for the tunnels under consideration.

When the bricks were cut to suit the shape of the skewback, they were cut in the following manner, which saved a deal of time as well as waste of

the material. A number of them were placed in a box (which was purposely contrived) and then wedged or screwed up tight; they were then cut with a stonemason's saw, working through a saw kirf in the opposite sides of the box, at the required angle, in a similar manner that a joiner cuts the mitres of his mouldings. This method answered very well, and had been previously used by the author for cutting bricks to the proper angle for the face of oblique arches.

When the invert and skewback were completed, the side wall moulds were set up, by simply placing them in the situation shown in fig. 2, and at o o, fig. 1, Plate III., and fixing the cross bar or stretcher, F, at the top; thus completing the leading frame, which was then set upright by the plumb lines, K K, and also central, by suspending from *e* a plumb bob, *d*, which should hang vertical over the centre line, as marked on the lower stretcher, G; it was then secured in its position by dogs driven into it and some of the props and sills, and by pieces of board wherever they could be advantageously attached.

The wall moulds were made of Dantzic, 3 inches in thickness, and were fitted on the skewback of the ground mould by having at their lower end an iron cap, containing mortices that fitted on the corresponding iron tenons, on the plates of the skewback of the ground mould; by this means it could be shipped or unshipped most readily. The subjoined engraving shows this part at large.

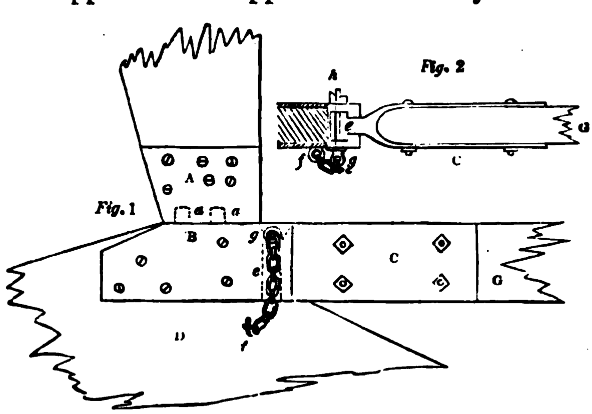


Fig. 1 is an elevation, and fig. 2 a plan, of that part of the leading frame which forms the skewback of the inverted arch, or the point where the side walls rise or spring from the invert.

A is the cap before spoken of, on the lower end of the side wall moulds, having mortices at the under side, which drop over two iron tenons, *a a* (shown by the dotted lines), which rise above a plate screwed down to the invert mould, as its skew-

back. B, fig. 1, is the skewback plate—there being a corresponding one at the other side of the invert mould. These plates are so formed as to make the socket into which the end of the stretcher, G, is dropped; its ends being made to correspond thereto by a cap, C, which is bolted through the wood. At *e*, fig. 2, is shown, in plan, the end of the stretcher when in the socket above spoken of; *g* is an iron pin passing through the socket, above the end of the stretcher, and retains it in its place. The pin is secured against working out by a cotter, *h*, on the other side, and from being mislaid or lost when not in use, by a chain attached to a staple, at *f*.

The top bar, or upper stretcher, of the leading frame, F, Plate III. served to connect the upper part of the frame, and to keep the top ends of the side wall moulds at the proper distance apart. It was in one piece, 5 inches by 3 inches, and was notched into the side walls, and secured thereto by iron plates, which were bolted to the stretcher, and projected over the moulds on each side. A pin was then passed through the overlapping ends and the moulds, similarly to the pin, *g*, in the last engraving, and was in like manner secured from being lost, when not in use, by chains attached by staples to the mould.

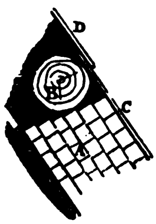
The brickwork of the side walls to the springing of the arch was then constructed outside the moulds, E E, or between the moulds and the earth, in English bond, with neatly-drawn joints. As the brickwork advanced upwards, the bars that had supported the earth were removed, together with as much of the poling-boards as could be got out. At Blechingley the work was built solid against the earth wherever there was more space than was necessary for the insertion of the intended thickness of the brickwork; but at Saltwood, such vacuities were rammed solid as the work advanced. Whichever of these plans may be adopted, it is of great importance that it should be carefully executed; it should, therefore, in all cases, be well attended to.

Above the leading frame, in fig. 2, Plate III., there is a dotted curved line that shows the intended under-side of the brickwork, or the position that the tunnel would occupy with respect to the timbering of the excavation.

When the walls were up to the height of the springing, the centres were set for turning the arch. The form, and all the particulars relative to them, will be reserved for a separate chapter, and it is therefore only necessary in this place to refer to fig. 3, Plate III. for their appearance when set, and of the brickwork of the side lengths completed. The left-hand portion of fig. 1 is a longitudinal section of the same work.

The brickwork of the arch consisted of a series of concentric half-brick rings; and where the joints became flush and straight, a heading, or bonding course, was inserted throughout the length of the arch; and care was taken that the bricklayers should preserve the true form of the arch in every ring of which it was composed.

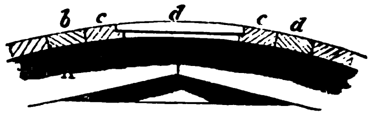
The manner of removing the bars which supported the earth, as the upper part of the side walls and the arch was advanced, is shown in the



adjoining cut, where the brickwork, A, is represented as brought up as far as the bar, B; and, before it can be advanced any further, the bar must be removed. The brickwork is built close up to the poling-board, C, which retains the earth, and also overlaps the front of the poling, D; it is therefore clear that the brickwork would hold both the polings in their places, and the bar which before held them might be removed without danger; for, even when the ground is bad, no movement could well take place in it before the brickwork would be further advanced, and render the poling-board, D, still more secure. In no case should the bars be removed until the brickwork is ready to supply its place without delay. In this way each of the side bars were removed, one by one, and laid aside to be used in the further progress of the work. A considerable number of poling-boards were necessarily built in, where the ground was not good and their removal could not be effected without risk.

The brickwork of the arch was brought up equally on each side, towards the crown, until it assumed the shape shown in fig. 3, Plate VII.; where A A is the brickwork of the arch. At this stage of the work, the laggins, C C, which are rabbeted on the top of their inner edge, are placed on the centres. In these rabbets, cross laggins, *d*, about 18 inches wide, are placed, one at a

time, beginning at one end of the length. A bricklayer then (standing with his head and shoulders between the two sides of the brickwork, A A) keys in the arch over the first short cross or keying-in laggin; which done, he places a second cross laggin in the rabbets of the long laggins, *c c*, and in like manner keys in that portion of the arch; he then places a third cross laggin, and keys in, as before, retreating backwards along the narrow space between A A, as his work advances, until the whole of the length is completely keyed in. These keying-in laggins are also represented in the annexed cut—which is a section through the laggins—where A is the top of a



centre rib; *b b* ordinary laggins, which were battens, 12 feet long, 6 inches wide, and 3 inches thick; *c c* are the rabbeted laggins extending the whole of the 12-feet length; and *d* one of the keying-in laggins fitting in the rabbets.

Fig. 4, Plate VII. is a longitudinal section, showing the same work, and also the manner in which the end of a length is left, with respect to the timber props and bars. F is the projecting end of a bar, to be drawn forward for the next length; G is the back prop, and H the permanent prop, as described at page 100. The whole of the brickwork was set in Roman cement.

After the completion of the side lengths, only one leading frame is required to go forward on each side of the shafts, as the work advances, because the brickwork already inserted becomes, as it were, the back mould to be worked from; therefore, as in each shaft four leading frames are required at first, and subsequently only two, the work may be so arranged as to obviate the necessity of making double the number of frames. This may be done by fixing those ground moulds that are next to the timbering of the shafts at a little distance therefrom, by means of wedges, which may be eased and drawn after the brickwork is in, and thus the frame may be set free; for otherwise the brickwork would jam the frame so tightly against the timbers that it would be impossible to set them at liberty until the shaft lengths were excavated, which is never done until both the side lengths are completed.

If, however, it should be considered the more secure method to build

tight against the mould and the timbers, to steady them when the ground is heavy, the moulds must remain until released after the completion of the shaft lengths; under which circumstances, additional leading frames must be made, or some of the shafts remain till the side and shaft lengths of others be finished. No moulds are required for the shaft lengths, as the brickwork of the two side lengths must be worked to.

Fig. 3, Plate III. is a cross section of the brickwork of the side length when completed, with the centres and laggins under the arch; and the timbering of the face of the excavation, also the crown bars, F F, &c. above the arch, intended to be drawn forward when the leading lengths shall be proceeded with, or left to remain, according to circumstances. Between each of these bars, a pier, *c*, or what is called a packing, is built, as the work proceeds, to relieve the bars from the superincumbent pressure, if it should be deemed advisable to draw them. The left-hand side of the shaft, fig. 1, shows a longitudinal section of the above-described length in brickwork.

Upon an inspection of fig. 3, Plate III. seven crown bars appear to have been built in, and counterforts or packings of brickwork, *c c*, constructed between each two of them. In all cases these bars were closed in above the arch, and remained there until the shaft lengths were completed, because they could not have been previously drawn; and no good purpose could be answered by so doing; on the contrary, the disturbing of them might have endangered the rest of the work. When, however, the first leading length was excavated, these bars were, in some instances, drawn forward, to be used for the crown of such length. The manner of doing this will be explained in a subsequent chapter, when describing the leading work. But in every case where symptoms of much pressure were present, it was considered prudent to leave the bars of the side lengths wholly undisturbed, as it was better to lose them than run any risk by their removal.

The bricklayers should be closely watched during the whole time they are at work, to see that they do it in a sound and satisfactory manner, as upon their labours the future stability of the tunnel depends. In no part should more attention be paid than while they are constructing the invert, for as much depends upon its strength as upon the arch above; and too

frequently this is considered by the workmen as of minor importance; and, as it is more out of sight when done than other portions of the work, it has a corresponding chance of being slurred over. In many cases, the low price that the men are paid for their task-work leads to their hurrying it over to make up their wages, and in other cases, where they have been well paid, unless they have been looked after, the chance of making greater gains has been their inducement to slight their work. The system of sub-letting the work, and then again sub-letting it in detail, wherever it is practised, invariably has an injurious effect upon the soundness of the construction.

CHAPTER X.

CONSTRUCTION OF THE TUNNELS, CONTINUED.

THE SHAFT LENGTHS—EXCAVATION AND BRICKWORK.

EXCAVATION.

UPON the completion of the second side length, the excavation of the earth from under the shaft, for the insertion of the shaft length of brickwork, should be proceeded with as rapidly as circumstances and sufficient care for the safety of the shaft will admit of. This, like the other portions of the excavation, is commenced at the top, and continued downwards. As the whole space beneath the shaft, to the full width of the tunnel, must be cleared away, it is evident that the square timbers, which had hitherto assisted in carrying the shaft, must be removed also; their removal leaves the shaft to be supported or suspended wholly by the shaft sills, as at Blechingley; or by the hanging rods, as at Saltwood; or by whatever other means may have been resorted to for that purpose. It is therefore incumbent on the miner to provide, as speedily as possible, other means of assisting to resist the downward tendency of the shaft, until it can be securely connected with the crown of the tunnel by means of a curb of brick or cast iron. The only support that can be given thereto (without encumbering the space where the men are at work) is by propping from the projecting ends of the crown bars of the side lengths, and from the upper bars of the shaft length, as they are inserted; and in this way ample strength may be obtained for the purpose.

The mode of timbering a shaft length is very simple, and consists in placing the bars with their ends resting on the back of the arch of the two side lengths already completed, and poling behind them, to secure the earth

from moving. Plate IV. represents a shaft length, as completed ready for the bricklayers; fig. 1 is a longitudinal section, and fig. 2 a tranverse section through the middle of the length; and, consequently, each section is taken through the centre of the shaft. Fig. 1 shows the two finished side lengths, A A′, and the wide space between them (or the shaft length) supported by the timbers, as above described. B B B, &c. are the bars, whose ends are passed behind the brickwork of the lengths A and A′, whereby they are secured in their places. *s s s*, &c. are the short stretchers between the bars which keep them steady, and connect them for mutual support. The poling-boards are also shown in place. C C are the crown bars of the side length, the ends of which project beyond their own brickwork, and thus supply a base, from which to prop the sills, or curb, that carries the shaft. At Blechingley the under sides of the shaft sills were thus supported; and at Saltwood, in the absence of such sills, the suspended square frame, or setting, upon which the wooden curb temporarily rested, was supported. *a a* shows two of the props thus carried by the ends of the crown bars (C) of the side length. In addition to this, more help may be obtained by propping from the upper bars of the shaft length, as shown at *a′ a′*, fig. 1, which are props supported by the upper bar, B′. In this way the shafts were supported, both at Blechingley and Saltwood, until the brickwork could be completed to take the weight of the shaft.

The transverse section, fig. 2, Plate IV. being taken through the middle of the length, cuts through the bars, B B, &c. and shows an end view of the brickwork of the side length, A A, which is left in toothings to be united with that of the shaft length. The same letters of reference in the two sections refer to corresponding parts of the work.

During the excavation for the shaft length the centres that are under the side lengths, A and A, together with the timbers connected therewith, should remain undisturbed; but the miners' sills (D and E, fig. 1, Plate III.) which were against the shaft, must be removed, with the earth that they abutted against; and in doing this, the stretchers, M M (Plate III.) between the miners' sills must also be removed. But before the removal of either the sills or the stretchers it is necessary to secure the timbers of the face of the excavation

from the possibility of their being forced inwards by the pressure of the earth behind (especially if it should, as at Blechingley, expand). This security is to be obtained by fixing two raking props, D D, Plate IV. against the lower miners' sill; the upper end of the prop being cut in the form of a bird's mouth, to receive the angle of the sill, and strongly hooped, to prevent its splitting; the lower end must be firmly bedded, and wedged into a hole made for that purpose in the brickwork of the inverted arch.

Figs. 1 and 2, Plate IV. show the raking props in place, of which there were always two against the lower sill at each face; and at Blechingley there was occasionally a necessity for two others to be set against the upper sill, and which are shown in Plates VI. and VII. At Saltwood it was generally found sufficient to use one pair of rakers against the middle sill only; but in all cases, after the completion of the side and shaft lengths, and in advancing the leading work, four rakers were invariably used, at both the tunnels, for the two upper sills at every face of the excavation.

BRICKWORK.

After what has been stated in Chapter IX. but little remains to be said of the brickwork of the shaft lengths. The sumps under the shafts were carefully filled solid with dry earth or with concrete, according to circumstances, and upon this the inverted arch was constructed.

When the side walls were built the arch was turned upon four centre ribs, *a a a a*, fig. 1, Plate V. in which the mode of executing the brickwork of the shaft length is shown. The three ribs under each of the side lengths were left in their places, undisturbed, until the shaft length and also the first leading length, were completed. At Blechingley there were ten centre ribs used in every shaft—five in each direction; so that, when the four ribs were lowered for turning the shaft length, they were not again raised to the surface (except for the purpose of repairs), until the work was completed. These four ribs, together with the three under each side length, made the required ten; of which five were advanced, as the work proceeded, in one direction, and the other five in the opposite direction.

It has sometimes been the practice, for the sake of economy, to use but six centre ribs in a shaft, instead of ten; and, for the purpose of turning the shaft length, to remove the two back ribs, *b b*, fig. 1, Plate V. from each of the side lengths, and place them under the shaft length, in the position *a a*, &c.; then to re-adjust the two ribs, *c c*, nearest the edge of the shaft, to take the ends of the laggins for the shaft length to be turned upon. By this practice the side lengths are left without any assistance, at a time when they are least of all capable of bearing any great strain; and, while thus standing alone and unsupported, they have to carry, not only the weight of earth that is fairly their due, but also the weight or pressure of the earth upon the bars of the shaft length; and, in addition thereto, have to sustain the weight of the shaft itself.

The safest practice is in the use of the greater number of ribs; and those were arranged as shown at fig. 1, Plate V. The three ribs under each side length, remaining undisturbed, were a great assistance to the brickwork in resisting any great pressure. And further, the two ribs, *b b*, on each side, were continued in their places until the first leading length each way was also completed: for as three ribs only were required for each leading length, two of the four ribs, *a a*, were moved forward each way from under the shaft to the advanced work, and the back rib, *c*, was all that was taken from (or disturbed in) the side length to make the three ribs required for turning the arch of the first leading length. And furthermore, the ribs, *b b*, were still continued in their places, undisturbed, until the side walls of a second leading length were constructed, and ready for the centres; which walls acted as buttresses against the new work when the two ribs, *b b*, were removed; and were well calculated to resist any tendency to derangement in the work.

In the foregoing manner the side lengths were well sustained during the whole time they were exposed to more than their fair share of pressure; and the same mode of advancing the work, with five centre ribs each way from the shafts, was carried on throughout the tunnel at Blechingley, without the least accident or undue settlement in the arch or side walls.

To determine upon the adoption of the use of either ten or six centre ribs, depends upon whether or not it be considered that the extra expense

attending the former method more than counterbalances the risk incurred by using six ribs only: the risk not being confined to the construction of the shaft length, but lasting until the work is finished. And it is not improbable that the cost of setting to rights one broken length would exceed the whole extra cost of the centres, laggins, &c. for any one shaft; independent of the doubt (to say the least of it) that attends all work done where there exists any chance of failure.

When the arch is turned the shaft is permanently connected therewith by a curb, either of brickwork, or cast iron made and put together in segments. The former was used in the works now under consideration, and is shown at figs. 1 and 2, Plate V. For these curbs the bricks were purposely made of the required shape; the angular bricks, where the shaft joins the soffit of the arch, were made large and rounded off, as shown in the engraving; these bull-nosed bricks (as they were called by the workmen) not only gave the work a better appearance when finished, but the arris being thus taken off, it did not injure the gin rope, in its subsequent ascending and descending; neither was the curb so liable to sustain injury by the striking of the skips.

Curbs of cast iron were used by Mr. Stephenson in the tunnels on the London and Birmingham Railway, and the engraving, Plate XII. represents them in detail.

Fig. 1 is a plan of the curb, as it is fixed ready for the support of the shaft. It is made in four segments, which are fitted and bolted together at *a*, *b*, *c*, *d*. The clear diameter of the circular area, formed by the curb, is the same as that of the shafts, 9 feet; and the top of the curb is a level surface (or flat ring) 1 foot 3 inches wide, and upon this the brickwork of the shaft rests. The dotted circular line shows the junction of the curb with the brickwork, as it appears from below, and corresponds with the point *e* in each of the other figures.

The brickwork of the shaft is built flush with the inner edge of the curb.

Fig. 2 is a section taken through the curb, upon the line, A B, of the plan, or at right angles to the direction of the tunnel. (This section corresponds with that of the brick curb, shown at fig. 2, Plate V.) The under side of the figure represents the soffit of the arch, and the line, *e f*, is the skewback sup-

ported by the brickwork of the tunnel, E. The line *e f* is, in this part of the curb, at its greatest obliquity, or makes its greatest angle with a vertical line; from thence its obliquity gradually diminishes (each way) throughout a quarter of a circle, or to the crown of the arch in the direction of the tunnel, where the line, *e f*, becomes perpendicular.

Fig. 3 is a section on the line, C D, of the plan, and is at right angles to the section in fig. 2. The line, *e f*, in this figure, where it joins the brickwork of the arch, E, is, as above stated, perpendicular. (This section corresponds with that of the brick curb shown at fig. 1, Plate V.)

Fig. 4 is a back view of the curb, looking at it in the direction A B, and shows the manner in which it is formed to abut against the courses of the brickwork of the arch.

Fig. 5 is also a similar back view, but taken in the direction C D, or at right angles to the last figures.

The curb is cast with chambers, in order to combine lightness with the requisite strength.

A plan of the brick curb is given at fig. 3, Plate V., and by comparison of the two sections in that plate with the engraving, Plate XII., together with what has been stated upon the subject, there can be no difficulty in comprehending the whole of its details.

The five bars nearest to the crown of the shaft length were built in, and left, as shown in the transverse section, fig. 2, Plate V. In this plate the manner of finishing the shaft, where it joins the arch of the tunnel, and of underpinning the shaft sills, at Blechingley, are fully shown.

At E, fig. 2, is shown the manner in which the skewback of the invert of the tunnel was constructed, as regards the form and arrangement of the bricks.

CHAPTER XI.

CONSTRUCTION OF THE TUNNEL, CONCLUDED.

THE LEADING AND THE JUNCTION LENGTHS—EXCAVATION AND BRICKWORK.

THE LEADING LENGTHS.

WHEN the shaft length is completed, the curb inserted, and the brickwork made good to the shaft, the centre ribs and the laggins may be removed from beneath it; but those under the side lengths should not be disturbed until after the first length forward is completed, for prudential reasons, explained when treating of setting the centres for the shaft lengths, at page 117, and which will again be alluded to when the centres and method of using them are described in a subsequent chapter.

The side lengths at Blechingley and Saltwood were 12 feet long, and so situated as to leave between them, upon an average, 14 feet for the shaft length; the three lengths making together 38 feet of tunnel under every shaft, from which to carry on the work in both directions. When this portion of the work is done, the difficulties of the tunnel may be said to be over, as the subsequent proceedings are comparatively straightforward and safe; at all events, there can be but few natural difficulties that cannot be foreseen, and consequently their effects provided for or guarded against; unless by injudicious proceedings, or absolute carelessness, difficulties and dangers arise which otherwise would not have existed.

Previously to commencing the leading lengths, it is requisite to construct a platform over the invert of the lengths already completed, as shown at P P, Plate IX. and which platform must be continued each way as the work advances. It is made of planks, laid on sleepers or transverse timbers placed across the invert, so as to leave a free channel for the water to pass

along the invert, to be drained off through the heading; or, in cases where the water is not abundant, it may hence be conducted to a proper receptacle or sump, convenient for the workmen to use it in mixing their cement or mortar; for where there is no water in the tunnel, the conveyance of that material to the shafts for the bricklayers' use forms a considerable item of expenditure. This was partly the case at Blechingley; the water, which was in abundance at first, diminished in quantity as the work advanced, and towards the last (except at the west end) the land springs appeared to have been drained nearly dry.

The more immediate use of the platform is to make a uniform plane, on which to lay down a temporary double line of rails, to run the wheeled skips (described at page 62) upon, from the face of the excavation to the shafts and the empty skips back again; one line being used as a going, and the other as a returning road. The rails at Blechingley consisted of pieces of quartering, with hoop iron fastened along the inner edge of the upper surface, for the wheels to run upon, and were before named at page 65; the roads so formed were frequently out of order, and in all probability it would have been better, in the first instance, to have provided some light wrought iron railway bars for the purpose, which, although much more expensive in their first cost, would have saved a deal of annoyance afterwards. The platform is shown in the engraving, page 100, where one man is represented as pushing a loaded skip towards the shaft, and another filling an empty skip with the débris cast down by the men above, who are excavating for the insertion of the second sill of a leading length.

The process of driving a leading length is nearly the same as that described for a side length; with the difference, that the bars in this case have to be propped and supported, at both their ends, whereas, in the leading work, they only require such assistance at their remote end, or against the face of the excavation—the near or back end of each bar being left to rest behind or upon the brickwork of the arch already turned.

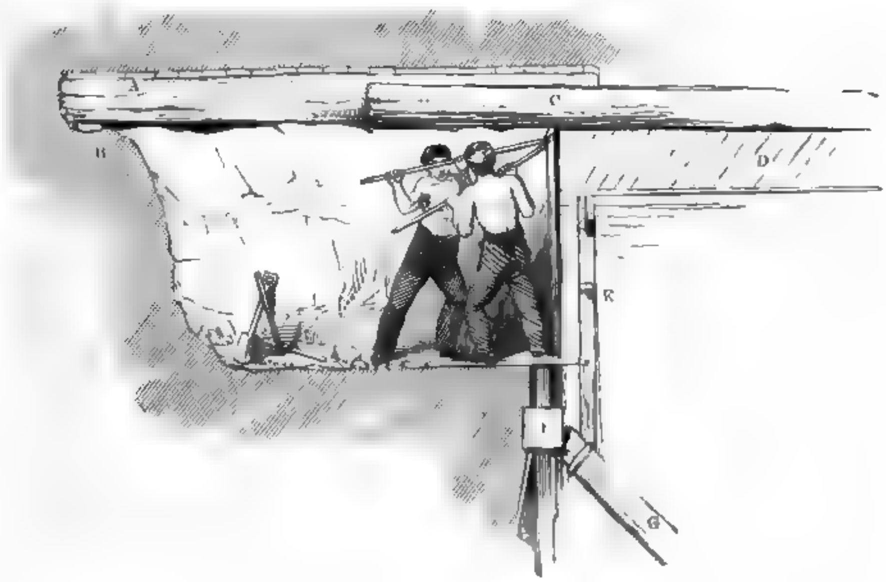
The work is commenced by getting in the top, in the manner described as for the side length. A top heading is driven in the middle line of the tunnel, for the insertion of the crown bars, and is then widened out to the

right and left, and the bars inserted one by one down to the level of the top sill. It will be remembered that the crown bars for the leading lengths were described as left above the brickwork of the side length, to be drawn out (of their cells) to form the roof of the leading work, length after length; by which means the same bars travel along the roof to the next junction, unless by accident any of them get broken, or stick fast in some part of their journey; whereupon they are generally built in and left. It is, however, not the safest of practice to draw the crown bars from the side lengths at all, but to build them in, and leave them, unless the ground is very good, when their removal would be attended with perfect safety. They were mostly left in at Blechingley, as their value was of trifling importance compared with any risk to the security of the work that carried the shafts, through disturbing the earth thereabouts; for, although the space from whence each bar is drawn is, professedly, rammed solid with earth by a man standing at the end where it is drawn, using a long-handled punner—yet, however well and carefully this may be done, it would, in most cases, be better that the bars were built in than that the surrounding earth should be in any degree disturbed; and, too often, if the men are not watched, they will omit the ramming altogether, as their neglect cannot be detected afterwards.

The next engraving represents the process of drawing the crown bars, whether from over the side or any subsequent leading length. The top heading is shown as having been already driven, and one bar, A, drawn forwards, and its advanced end resting upon the shelf of earth, B, preparatory to its being propped; the ground is also shown as ready for another bar, C, which the men are drawing from over the brickwork of the last turned length, D; the leading centre rib, E, is shown in section under the brickwork, also an end view, F, of the top sill, and the upper end of its raking prop, G.

The drawing of the bars can mostly be accomplished with crowbars used as levers, as shown in the next engraving, which brings them forward by little and little, till the larger portion of them is advanced, and then they come out easily enough; but if, during their confinement above the

brickwork, any particular settlement has taken place, the bars will frequently be jammed in extremely tight; the only way then to release them is by the use of one or more screw-jacks placed horizontally against the arch, and lashing chains passed over these and also round the projecting ends of the bars, when, upon working the screws, the bars are released. If, however, the resistance is too great to be overcome in this manner, the bars are left and built in; for where a settlement has been so great as to cause such an effect, it would probably be unwise to draw the bars at all, were it



even possible to do so, lest a movement be given to the earth that would be liable to produce results far more costly than the value of a few bars.

When the bars are drawn, great care should be taken, as before stated, that the space from whence they are removed is packed and rammed solid with earth; for the danger of leaving an empty space above the arch is too obvious to need any remarks. It is also of importance that attention be paid to the amount of sinking that takes place in the top of each length whilst standing in timber, in order that the leading ends of the bars for the succeeding lengths may be raised sufficiently high above their required level to allow for their sinking before the arch is turned.

It will be easily understood that, where so large an excavation is entirely supported by timbers, in comparatively small pieces, resting upon and pressing against each other, without being one piece of framework well braced together, there must be some general or particular settlement in its parts; and this, as might be expected, takes place very much in the roof. If, therefore, the bars are raised sufficiently high above their required level, and such settlement takes place, they will merely descend to their proper places; and if the amount of sinking that is thus provided for does not occur, it is but of little consequence, as the space can be packed solid, and a more correct allowance for it be made in future. If, however, sufficient allowance has not been made, the bars will sink into the space that must be occupied by the brickwork of the arch; in which case, when the arch is brought up to that place the bars must be raised, by excavating above them by little and little, which is attended with inconvenience and additional expense. The arch forms the gauge to direct the miners in placing the bars. This subject has been named before, in connection with the side lengths, page 92, but its importance in every stage of the work will be a sufficient excuse for referring to it again.

The engraving at page 100 is a section of the tunnel, with a leading length in progress. The last two completed lengths are left resting on five centre ribs, supported by their props. The whole of the timbering of the top of the new length is represented as complete down to the first sill; and the excavation is proceeding for the insertion of a second sill, which is shown as standing in its last place against the toothing end of the finished length, supported by its props; from whence it will be shifted forward, as soon as the excavation is ready for its reception.

The whole of the operation of timbering and bricking the leading work is shown in Plates VI. and VII. Fig. 1, Plate VI. is a section through the timbering at the line, A B, fig. 2, and shows the face of the excavation, with its sills, bars, props, &c. &c. with a leading frame, O, set ready for the bricklayers; fig. 2 is a longitudinal section of the same thing. It will be observed that the timbering is not shown to extend lower than the bottom sill, except in the central part, R, around the heading of the tunnel. This is the manner in which a large portion of Blechingley Tunnel was done; the ground being

sufficiently good for the lower parts to stand without assistance, during the short time it was exposed, until the brickwork was inserted; but this in no case applied to the upper part, which had a much longer time to stand before it could be permanently closed in. It was always the rule never to let a length wait for the bricklayers, but to have them and their materials ready to proceed immediately that the excavators had done, and the ground mould set; thus the lower part of the length being the last exposed, and the first closed in, stood but a short time without assistance.

The leaving the lower part of the excavation without being timbered was not general throughout the tunnel, and in no case around the heading, where the ground was always loose, having been previously disturbed when the heading was driven. The method and extent of timbering about the heading is shown at R, fig. 1, Plate VI. At Saltwood Tunnel, as well as in some parts of that at Blechingley, the timbering was continued to the bottom, as it must be in all loose ground—and is shown in Plate VIII. and several other engravings.

The timbering of the side and leading lengths are nearly similar to each other, with this chief difference, that in the former several stretchers were fixed from sill to sill, horizontally, along the length, as described at page 97, to keep the back and forward sill from collapsing, or the face of the excavation being pressed inwards; but in the leading lengths no back sills are required, as the completed brickwork makes all secure overhead at that end of the excavation; in order therefore to prevent the pressure of the earth forcing the sills and timber of the face inwards, and bringing destruction upon the whole length, two raking props are applied to each sill, notched at the upper end to fit its angle, and wedged at the lower end in a hole purposely left, or made in the invert, and thus the thrust of the face is resisted. An inspection of each figure representing the leading work will make the explanation perfectly clear. D D and D′ D′, in each of the figures in Plate VI. are the raking props. These raking props have also been previously alluded to at page 98.

A longitudinal section, showing the brickwork of a length completed, is shown at fig. 1, Plate VII.; and fig. 2 is a transverse section taken across the said length, or on the line A B, fig. 1.

After all that has been before stated respecting the manner of excavating and constructing the side lengths, it would be but a recapitulation to go through the details of that of the leading work—the *modus operandi*, in both cases, being so similar that an inspection of Plates VI. and VII. after reading what has before been stated, must show to every intelligent reader the whole business.

Before closing this part of the subject it should be observed that where the forward ends of the bars, in the leading lengths, abut against the face of the excavation, they should be well chogged, or rather tightly wedged, against the earth, allowing the bar no interval or room to play in the direction of its length. This is especially necessary where the ground is loose, as sand, or yielding, as soft clay; for as the tendency of all leading work is to settle, or press forwards, in the direction that the work is being driven, the earth in front of the said bars is liable to yield when the pressure is great, and if it does yield the whole length goes forward that much, and is liable to drag the last turned length with it, and thereby cause a fracture in the brickwork where it joined the preceding length.

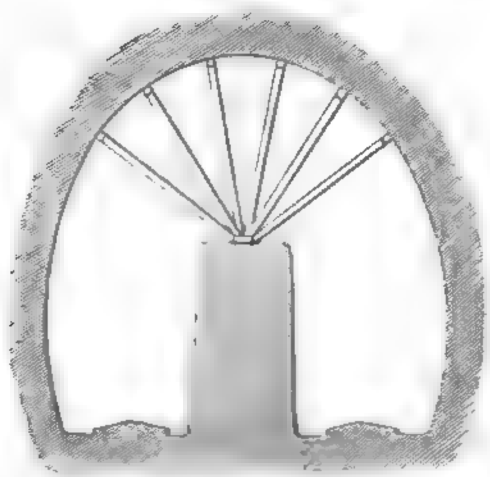
This kind of accident occurred at Saltwood Tunnel, where the negligent workmen had even left a space between the ends of the bars and the face of the work, which caused the lengths so circumstanced to go forward, and drag with them the last length of brickwork, breaking it away from the preceding work, and brought so much weight thereon as not only to break the brickwork, but also to break the bars themselves. No such accidents happened again, for care was taken that the ends of the timbers were closely abutted (by wedges if necessary) to the face of the work. The necessity of always keeping the work tight against the earth, to prevent the possibility of its moving, must here be again impressed upon the practical man; and it should be an invariable rule never to leave a vacuity behind the work.

The quantity of timber required for any tunnel work will depend upon the character of the ground. In the works at Blechingley, which have been described, two miners' sills only were used; the ground at that place was neither *good*, nor, taken as a whole, *very bad*; if it had been a little heavier, or in other words, have pressed more heavily on the work, three sills

would have been used in each face instead of two. The extensive use of timber is to be avoided as much as possible where it can be safely omitted, because it increases the cost of the works, not only by the price of the timber, but for additional labour in inserting and removing it. But in no place should be practised a penny-wise economy in the use of materials, as that frequently results in pounds of subsequent expenditure. Experience and judgment will decide as to the extent of timbering necessary.

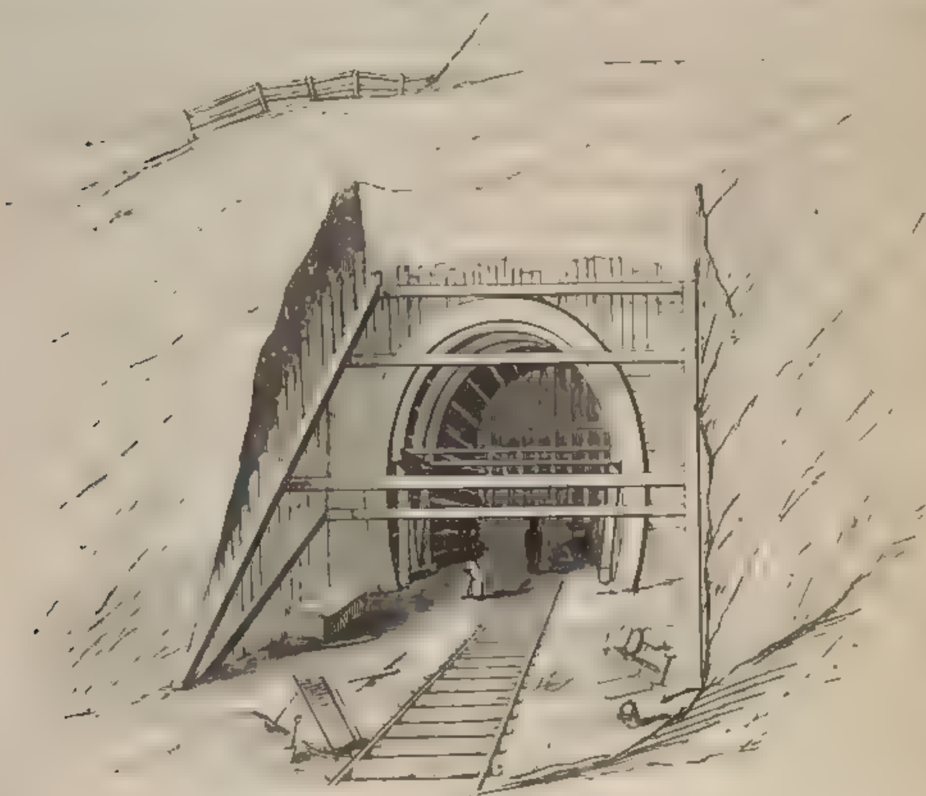
When three sills are employed, as at Saltwood Tunnel, the mode of operation need not be altered from that already set forth; and an inspection of Plate VIII. which represents the timbering adopted at Saltwood Tunnel, with what has already been stated, will give all the information necessary for the working with three sills; A, B, C, are the three miners' sills; *a a*, &c. &c. show the position of the stretchers, this being a side length; but, in other respects, it is the same as was adopted for the leading work, except the omission of the raking props.

Where the circumstances are such that the ground will stand with but little or no timbering, as is mostly the case with rock and chalk, the operation of tunnelling is of the simplest character. The only thing necessary to guard against is the first displacement of the strata, which can generally be prevented with very slight timbering, judiciously placed; if this is not watched, and done in time, a slip of the rock will frequently bring in so much as to leave a great cavern, which must be filled solid behind the work to make it secure from future danger. The annexed engraving shows the manner of timbering in constructing



tunnels of this description, and is similar to that adopted by Mr. Wright, in the construction of the Abbot's Cliff Tunnel, which was made through the lower chalk between Folkestone and Dover. The sides are first excavated, leaving a pillar in the middle, which serves as a base to prop the roof from,

and also to support the centres for turning the arch when the side walls are up; the pillar may then be cut away. But where an invert is to be inserted this mode of proceeding is inconvenient, and requires great care in propping the arch during the construction of the invert and the side walls for the underpinning of the said arch; because the centre pillar that has been left to carry the props and the centres must be removed before the invert



can be commenced, and that must be completed before the side walls can be constructed. This method has been practised to a limited extent, namely, excavating and constructing the tunnel from the top down to the springing; or, in other words, constructing the arch first, then excavating the lower parts, and, by constructing the invert and side walls, underpin the arch. Such a method of proceeding is better suited for rock and chalk tunnels where no invert is required, than for heavy ground, where an invert is indispensable; in which latter case considerable risk attends the operation. It

was however accomplished very successfully by Mr. Daniel Frazer in a large portion of the Martello Tunnel which he constructed near Folkestone for the contractors, Messrs. Grissel and Peto, through the junction of the chalk, upper greensand, and the gault, which latter stratum appeared in the lower part of a portion of the tunnel.

A small portion of the Saltwood Tunnel was driven from the open cutting at the west end, as the excavation was completed at a sufficiently early time for the purpose. Seven lengths of tunnel were constructed from the intended face, or entrance to the tunnel, when a junction was effected with the workings that had proceeded in the opposite direction from No. 1 shaft.

The mode of proceeding with the work from an open cutting is the same as for the ordinary leading lengths previously described; but considerable care is required in timbering the face of the excavation, before the driving of the tunnel is commenced, to prevent its falling in, and causing inconvenience and expense.

The method of timbering the face of the excavation at the intended western entrance to Saltwood Tunnel is shown in the engraving on the preceding page.

When the works were in this stage of progress, the temporary railway that had previously been used in making the open cutting was advanced into the end of the tunnel, as the work progressed. The earth that was excavated by the miners was filled into waggons and removed to a distant spoil-bank. The timbering and the construction were in all other respects the same as for the sub-excavation.

BRICKLAYERS' WORK FOR THE LEADING LENGTHS.

The brickwork of a leading length is shown in Plate VII. wherein fig. 1 is a longitudinal section, and fig. 2 a transverse section taken on the line A B, fig. 1, each representing the work as it appeared as soon as the arch was keyed in, and ready for the miners to commence excavating for another length onwards. In each of the figures the crown bars are shown at F, the packings in brickwork at *c*, the props at G and H. B′ is the arch of the length last completed,

and A′ is the arch of the preceding length; the line of junction between the two lengths being where the ends of the two sets of laggins meet, as at *f*, *g*. *a′*, *b′*, *c′*, are the three centre ribs supporting the laggins upon which the last length was turned, and *d′ e′* show the leading and middle ribs under the laggins of the preceding length, the third or back centre rib having been moved onward to the position *c′*. The two ribs, *d′ e′*, were left to remain undisturbed in the position shown in the engraving until the side walls of an additional length were built, when they, with the laggin, sills, props, &c. were moved onwards, as named at page 117. D and D′ are the raking props to the upper and lower sills. The wedges or slack blocks, the half-timbers, and the props (all of which belong to the centering), will be referred to and explained in Chapter XIII. which will be devoted to the particulars of the centres. Figs. 3 and 4 have already been referred to at pages 110 and 111, where the brickwork is generally described, under the head of the side lengths.

THE JUNCTION LENGTHS.

In the manner now described the tunnel works are usually carried on in lengths, as they are called, of 9, 10, or 12 feet, as the nature of the ground will admit of. Twelve feet is a convenient length in all cases where it can be adopted with safety, and this is done both ways from each shaft till the workings meet; the last length, or space required to join the two workings, is called the junction (or thirling). The length of the junctions should be brought as near to that of the ordinary lengths as possible, so that the same timbers may be used; for if they be much longer, the same bars will not reach across from brickwork to brickwork, to take a bearing for the support of the earth; and if they be much shorter, there will be a difficulty in drawing the last crown bars from the last length each way: and, what is of more consequence, if the earth left between the workings which form the junction is but a mere thin partition, it will probably give way before the last two leading lengths are turned; and this might be productive of at least unpleasant consequences. It is the safer practice, when approaching the junction, to stop one of the workings and advance to it in one direction

only; for if the work be carried on at both sides, there is great probability of disturbing so narrow a wall of earth as would then be left for the junction length.

The only timbers required for a junction length are bars and poling-boards. The bars rest on the brickwork of the preceding lengths, and are built in as the work advances. The side walls and the arch are constructed in the usual manner, together with the keying-in of the crown, as described at page 110, by the bricklayers inserting one cross laggin at a time, and closing each space over the said laggin, till at last the space is reduced to such small dimensions that he no longer can stand with his head and shoulders in it to do the work—as shown in the engraving below. He is therefore obliged in this last small piece to turn the top ring of the arch first, by fitting and wedging his bricks tight, in the best manner that he is able, passing them with his hand and arm up the opening, and bonding the top into the next lower ring, by some of the bricks put up as headers; then setting the next lower course or ring, bonding as before, and wedging it up tight; and so on with each course, until the opening in the bottom course, or soffit of the arch, will only be sufficient to receive one brick put endways into it; which brick, if necessary, must be tightly wedged into its place, with wooden or iron wedges, and the work will be finished. The whole of this final closing the work should be done with cement of the best quality. The space or opening left for this process need not exceed the dimensions of two cross or keying-in laggins. The an-

nexed engraving represents a bricklayer in the act of passing a brick up into its place through a hole left by the omission of two cross laggins in the manner above described. The closing portion, if properly done, is

never likely to fall out, because its sides are splayed from the opening upwards, each course being wider than the lower one; they are also bonded into each other as well as into the toothings of the arch at each end of the aperture, and the last brick is wedged or rammed tight into its place so as not easily to be dislodged, added to which there is the adhesion of the cement, which, if good, and properly gauged, possesses great strength.

WEIGHT OF BRICKWORK.

An experiment was tried, on September 3, 1842, to determine the weight of a cubic yard of brickwork. On the works at Saltwood there was an excellent weighing-machine, by Pooley & Son, upon which the experiments were tried.

BRICKWORK IN CEMENT.

	Tons.	cwt.	qrs.	lbs.
A cubic yard of dry bricks . . . . (384) =	1	2	1	20
Sand, water and cement for ditto	0	6	2	4
Total weight of a cubic yard of brickwork in cement =	1	8	3	24

BRICKWORK IN MORTAR.

	Tons.	cwt.	qrs.	lbs.
Bricks, as above	1	2	1	20
Mortar for ditto	0	4	1	8
Total weight of one cubic yard of brickwork in mortar =	1	6	3	0

CHAPTER XII.

TUNNEL ENTRANCES—SHAFT TOWERS—AND CULVERT THROUGH THE TUNNEL.

TUNNEL ENTRANCES.

It is unnecessary to state much upon the subject of the entrances, as it would answer but little purpose except to swell the volume. The designs for such constructions should be massive, to be suitable as approaches to works presenting the appearance of gloom, solidity, and strength. A light and highly decorated structure, however elegant and well-adapted for other purposes, would be very unsuitable in such a situation: it is plainness combined with boldness, and massiveness without heaviness, that in a tunnel entrance constitutes elegance, and, at the same time, is the most economical. The above conditions may be answered without cramping the taste of the Engineer, so far as taste enters into the composition of such designs; for architectural display, in such works, would be as much misplaced as the massiveness of engineering works would be if applied to the elegant and tastefully designed structures of the Architect. Upon the London and Birmingham and upon the Great Western Railways there are several very suitable structures of this kind.

The engraving on the following page represents the eastern entrance to Blechingley Tunnel, where the slopes of the open cutting are uniformly 2 to 1. The western entrance is similar in design; but the slopes of the open excavation differ from the slopes at the east end—being $1\frac{1}{2}$ to 1 on the north side, and (by means of level benchings) 2 to 1 on the south side, which arrangement of the slopes was occasioned by the tendency of the strata to slip on the one side of the cutting more than the other, and arises from its dipping from south to north, and from the general disturbance of

the beds, as explained at pages 15, 16. The quantity of brickwork in the wing walls of the one entrance is, consequently, greater than in the other: they are, however, similar in every other respect.

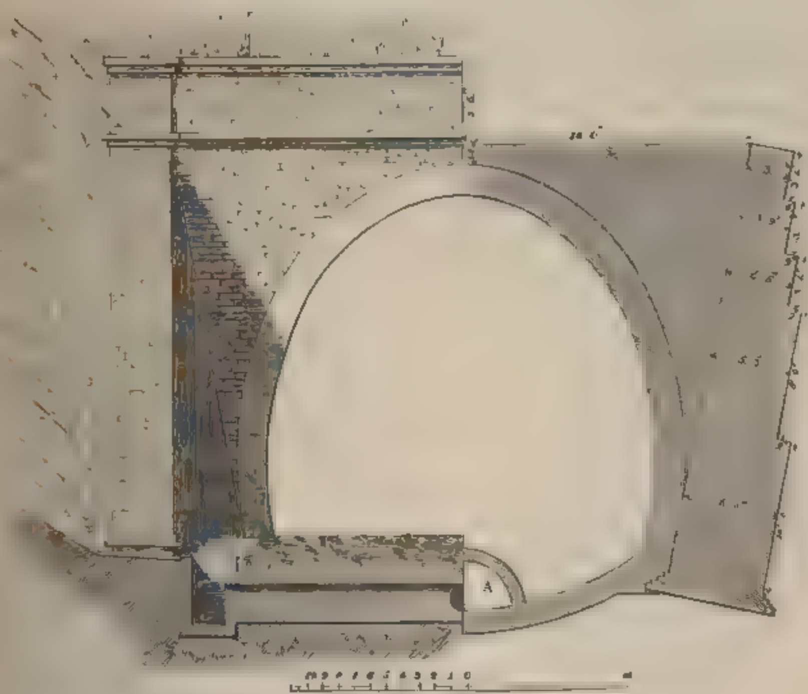
An inspection of the engraving will render it unnecessary to go into a minute description of the entrance, as the design is fully shown in all its parts. The whole is composed of bricks, no stone whatever being used in

BLECHINGLEY TUNNEL

the construction. Not but that the use of stone for the string course and the coping would have been preferable to bricks for those purposes; but no good material of that kind could be obtained in the neighbourhood, and its cost when conveyed from London (about 24 miles, by land carriage, over a hilly country), the nearest place from whence good stone could be procured, would probably have been greater than was due to the difference in the comparative quality of stone and bricks, for that purpose.

The plan of the wing walls is circular, being struck with a radius of 30 feet, and battered 3 inches to 1 foot. The pilasters are 6 feet, and

the plinth of the pilasters 6 feet 6 inches wide. The space between the pilasters, for the entrance of the tunnel, is 28 feet; and as the tunnel is 24 feet wide, the arch shows on the outside a thickness of 2 feet, and is formed of five half-brick rings. The space between the external contour of the finished arch, at the crown, and the under side of the string course, is 1 foot; the string consists of four courses of brickwork, and the height of the parapet, from the string to the under side of the coping, is 3 feet. The



thickness of the coping is 1 foot 3 inches. A brick open drain, along the back of the parapet, conducts the rain water to similar drains made down the slopes, and hence to the water channels alongside the railway, where it joins the drainage from the culvert within the tunnel (to be presently described), and passes off to the natural drainage of the country, at the tailing out of the open cutting.

The Saltwood entrance differs materially from that constructed at Blechingley, and is shown in the above engraving. The left-hand half of the

figure represents the elevation of half the entrance; and the right-hand half shows a section of the same.

The wing walls are not curvilinear, as at Blechingley, but are built straight, or parallel to the line of railway, and follow the slope of the excavation; they also batter at the rate of two and a half inches to one foot. The dimensions of the wing walls, parapets, &c. are given in the engraving on the preceding page.

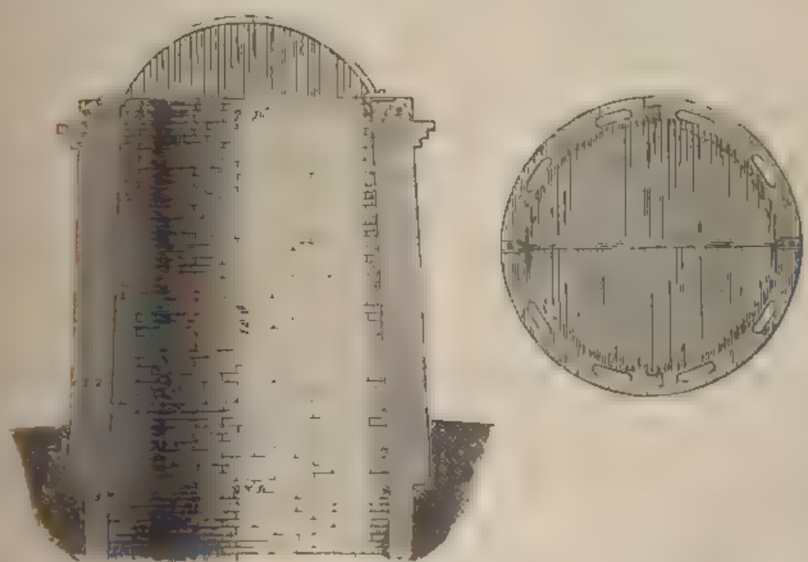
The following engraving is a section taken through the centre of the end of the tunnel, and shows a side elevation of the wing wall; and also a section of the barrel drain which conducts the water from the culvert that is constructed on the invert of the tunnel, throughout its length, similar to the one at Blechingley. A drain is also made along the back of the parapet and wing walls, to conduct the surface water to the proper drainage. By comparing the various parts of the preceding engraving with the corresponding parts of the following engraving, the details of the construction will be clearly apparent.

The erection of the entrances was paid for by the rod, of 306 cubic feet. The price per rod is not the same in all places, chiefly arising from the varia-

tion in the price of bricks. The quantity of brickwork in such entrances and wing walls as at Saltwood—where the slope of the earth is $1\frac{1}{2}$ to 1—amounts to 40 rods; and where the slope is 2 to 1 it will amount to 51 rods. This is reckoning for the work as shown in the preceding engraving; but where there is additional work, as counterforts to the walls, &c. it will of course exceed this. The quantity of brickwork in the Blechingley entrance amounted to 65 rods—the slope being 2 to 1—and the wing walls being much larger than those at Saltwood, in all their dimensions.

THE SHAFT TOWERS.

At Blechingley Tunnel all the shafts (with the exception of No. 11) were left open for the purposes of ventilation; and at Saltwood five were left open for the same purpose; the others were closed by doming them just above



the arch of the tunnel, and filling them with earth to the surface. For the prevention of accidents, the brickwork of the shafts was carried up to some height above the surface of the ground, in the form of a tower, as shown in the annexed engraving, and then covered in with an iron grating, which prevents stones falling down, if thrown for that purpose by mischievous persons.

The domed shape of the grating not only gives it strength, but would cause such stones to roll off again.

The towers at Blechingley and Saltwood were raised 12 feet above the level of the spoil-bank or where the brickwork of the shaft terminated. The shafts were of 9-inch work, but the towers were 14 inches thick; therefore where the towers commenced they sailed over, outwards, 4½ inches, as shown in the preceding engraving. The towers diminish upwards, from 9 feet at bottom to 7 feet 10 inches, inside dimensions, at the top.

The iron grating was made with a cast-iron circular ring, or plate, 9 inches wide, and an inch in thickness; with a lip around the inner edge that fits into the shaft, and keeps the grating from sliding from its bed. The plate was cast in halves, dovetailed together, when set in its place, as shown in the right-hand figure of the last engraving.

An arched rib passed over the grating, which was bolted to the plate, and, being also in two parts, was united in the middle by a half-lap joint and a bolt and nut. The wires forming the grating were five-eighths diameter, and were riveted on each side at the under side of the plate, and in the centre passed through the arched rib before named, which strengthened them and kept them equidistant apart. The cost of each grating, complete and delivered, was 6*l.* 10*s.*

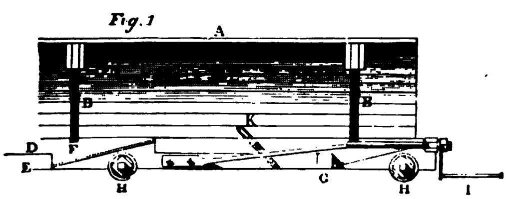
THE CULVERT.

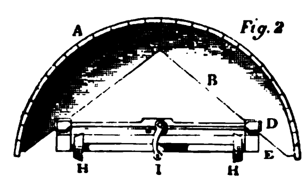
Along the centre of the invert of the tunnel a culvert was constructed to carry off the water, both at Blechingley and Saltwood; its form and position is shown at A in the engraving, page 135, of the section of half the entrance of Saltwood Tunnel. It was described with a radius of 2 feet 3 inches from the centre of the invert, and was therefore not quite a semicircle, because of the rising of the invert on each side of its centre. The brickwork was 9 inches in thickness; and at Bletchingley properly radiating or wedge-shaped bricks were made for it; they were 10½ inches long, 4 inches thick at the back, and 3 inches at the inner side, and 9 inches in breadth. To form the arch it required 26 of these bricks; and 90 were used in every

yard forward, so that for the tunnel (1,324 yards long) 119,160 were used in the construction of the culvert. These bricks cost 50*s*. per thousand.

The sides of the bricks were bedded in mortar, but their ends were set quite dry, which left sufficient space for the water to drain from the ballast to the culvert. For Saltwood Tunnel it had been the intention to have constructed bricks of a similar kind, but the works having been let to contractors, they used common bricks for the purpose, of which there were required 264 in every yard forward. The bottom courses, both of the culvert bricks at Blechingley, and the common bricks at Saltwood, were set in cement.

In order to facilitate the work, a centre was contrived 24 feet long for turning the culvert. This centre was fitted to a strong horizontal frame of





the same length, and 3 feet 3 inches wide; and the whole was fitted to a similar frame, or stage, movable upon rollers. The above engravings show this culvert centre. Fig. 1 is a longitudinal section showing six feet of its leading end, and fig. 2 is the elevation of the leading end. The laggins are shown at A, which were made of inch deal. The centre ribs are shown at B B, and were six in number, made of $1\frac{1}{2}$ inch stuff, and strengthened at the top by cross pieces, C. The upper frame is shown at D, and E is the lower frame; the upper one is movable upon the lower one, by sliding up the inclined plane, F, of which there are six on each side. When the upper frame is lying close upon the lower one, these inclined planes or notches resemble scarf joints. The frames are made of fir, 3 inches square, and are strengthened by cross ties, G, and diagonal braces.

The lower frame is movable on twelve rollers, H, &c. (six on each side), by which means it can easily be drawn forward as the work advances. I is a winch, the turning of which gives motion to a screw that is attached to the

upper frame, while its thread works in a socket attached to the lower frame; when the screw is turned it draws the upper frame forward, or causes it to slide lengthways upon the lower frame; but in consequence of its being notched, as it were, into the lower frame, in the manner of a saw-tooth rack, it must necessarily slide up these inclined planes, thus partaking of a compound motion, rising upwards as it advances forward; and when a reverse motion is given to the screw by turning the winch, I, the contrary way, the upper frame, with the centre, will recede to its former position, and in so doing it will descend the inclined planes, and hence take a lower level. K shows one of six iron guides that partake of the motion of the centre and keep it from moving sideways while it is being wound up, or the reverse.

By this contrivance the business of setting and easing the centre was greatly facilitated, and withal it was made twice the length that culvert centres usually are, thereby enabling the workmen to get on faster. In using it, the centre was first placed in position; the winch, I, was then turned, till the segment was raised to the required level, and upon this the arch was constructed, which completed a length of 24 feet; now, by reversing the action of the winch, the centre was lowered from under the brickwork, and was therefore released from its pressure, whereupon it was drawn forwards by two men (nearly but not quite) from under the 24 feet of culvert already completed; and, being placed in line, motion was again given to the winch until the centre was raised once more to the proper level, which could now be known by the end of the centre fitting up to and under the completed length; a second portion of the culvert was then turned, and the centre raised and moved forward, as before. In this manner the work proceeded rapidly, as the easing, removing and resetting the centre did not occupy more than two minutes; and when the men got accustomed to it they did it in but little more than a minute.

When the tunnel at Blechingley was completed, it was cleared out from end to end, and the invert examined and made good where the raker-holes and props had injured it. A scaffold was made to run upon wheels along the tunnel, by means of which all parts of the arch and side walls were carefully

examined, and its shape tested by a mould. Afterwards the whole was limewashed, with a view to add to the light of the tunnel, which, as before stated, was but of little service. The ballast for both tunnels was mostly the débris from the brickyards and the broken stone dug up from the temporary roads made on the works above. These were thrown down the shafts and spread at the bottom. On the top of this rough ballast a coat of finer material was used, about a foot in thickness, to bed the sleepers in; and the permanent way was then finally laid.

By means of the culvert above described, the whole of the water that might find its way into the tunnel was effectually carried off. The rough ballast that formed the bottom stratum was sufficiently porous to allow the water to pass to the culvert, which being built with the end joints of the bricks dry, admitted of the water percolating into the barrel of it, from whence it passed off to the drainage at the open end of the tunnel.

Towards the west end of the tunnel a considerable quantity of water entered through the roof at one place, and appeared likely to continue to do so. It was therefore necessary to provide for conducting it to the under drainage, instead of allowing it to drop into the tunnel. This was accomplished by cutting a chase in the brickwork of the side walls, and, from the top of the said chase, making a similar cut in the soffit of the arch to where the water was found to enter; then concealing the chase or gutter by bedding flat tiles in the front, to make the walls and arch of the tunnel appear perfect; this left a conduit or channel behind the tiles to collect the water that entered the tunnel, and conduct it down the sides, to the invert, and from thence to the culvert, by a small drain. The tiles were set in cement, and the whole of the face was then plastered with the same material.

When the water enters at more than one place, but at no great distance apart, it can all be gathered into one general drain by cutting oblique chases to collect and lead it to one or more outlets.

At the Martello Tunnel, near Folkestone, where a great quantity of water enters through the roof, it is conducted to the sides by lining the roof with sheets of corrugated zinc.

CHAPTER XIII.

THE CENTRES OF ORDINARY CONSTRUCTION—AND FRAZER'S PATENT CENTRES.

IN the preceding chapters all particulars of the centres were omitted when describing the brickwork, an important and interesting part of the subject. The reason for so doing was to prevent confusion by introducing too many subjects together; and as the account of the centres, and the method of using them, would occupy considerable space, it appeared better, for the general clearness of the subject, that it should be reserved for a subsequent chapter; it being sufficient, for the purpose of describing the brickwork, to state that the centres were set up, and the arch turned upon them. The particulars of the centres will now be given.

The centre ribs, that were made for and used in the construction of Blechingley Tunnel, were essentially the same as are commonly used in such works. It is frequently the case that contractors carry on their work with one set of centre ribs only, which must be taken from under the green brickwork to be set forward each time the arch of a new length is to be turned. As this mode of proceeding appeared objectionable, two sets both of centres and laggins were used upon the works under consideration, by which means all danger and injury thereto was prevented; and, although the additional cost of such set of materials was considerable, yet it probably saved a much larger sum that would have been incurred in repairing broken work, and ensured a sound tunnel.

When the Blechingley Tunnel was completed, the plant and other materials were conveyed to Saltwood for the purpose of being again used, and the centres were partially so; but upon that tunnel being let by contract, and the contractors having appointed Mr. Joseph Frazer as their representative, that gentleman introduced his patent centres, thus affording ample means for

observing and estimating the comparative merits of his centres and those of the ordinary construction, especially as they were being worked under the superintendence of Mr. Frazer himself. Particular attention was, therefore, paid to the subject, that the result might be satisfactory. A description of each system of centres, with the cost of their construction, will be given, and a comparison drawn between them.

THE BLECHINGLEY CENTRES. PLATE IX.

For each shaft of the tunnel there were required 10 centre ribs, 4 sets of laggins, 6 centre sills, 16 half-timbers, 40 props, and 40 pairs of slack blocks, or wedges; to these may be added a few wedges, and chocks, or chogs, &c. the timber for which is generally obtained from the offal timber which always collects in abundance on such large works, and therefore is not necessary to be named in an estimate. The above quantity of materials is required for working from each shaft in both directions; consequently one-half the above materials form a complete set, as used at Blechingley, for working in one direction, or as it is called 'one end of the shaft.' This will be described, as being all that is essential to the present purpose. It must be supposed that the side and shaft lengths are completed, and that the centres are to be applied to construct the arch of the leading work.

At each end of a shaft five centre ribs are required; two of them must have no tie-beams, as that would interfere with the raking props. These were called segment or leading centres; their construction and dimensions are shown at large, fig. 3, Plate IX.: they consist of two segments, and, when put together for use, are joined along the line a, b, and also by the movable tie, c; this tie prevents the spreading or contraction of the segments. This form of centre was found to be particularly convenient and strong, and, as the only doubt about its utility, for all tunnel purposes, might appear to be the want of a complete tie-beam at the bottom, this desideratum, if such it is, might be supplied by a movable piece, or iron screw tie, to connect the point d to the opposite point, d'; if this were applied it probably would, in addition to the convenience of shifting and resetting, sustain any amount of pressure ever

likely to occur, either vertically or laterally, and also all ordinary wear and tear and damage from the blasting of rock, and therefore would require little or no repair throughout a job. There is, however, an objection to movable pieces, as they are apt to be mislaid and lost; but, to prevent this, the men employed in the gang for shifting the centres should each be fined when a piece is lost, not merely to pay the value of the material, but also the loss of time sustained by the bricklayers and others, in consequence of such neglect. At Blechingley the strength of these ribs was fully tested; for, as they were the leading ribs, they were exposed to the greatest effects of the blasting, yet they never required any repairs, and after removal to Saltwood, by land and water carriage, they were uninjured; it would therefore appear that they are preferable to most of the ordinary centering.

The other three ribs were differently constructed, and were called scarf or queen-post centres. Fig. 4 represents them: in construction they are well calculated to sustain heavy weights. This form of centre has been before used in tunnels, as on the Birmingham and Brighton lines of railway. The tie-beam is a great security against the spreading or contracting of its span, but it is liable to interfere with the raking props supporting the face of the excavation. Another objection to this form of centre is that it is not well adapted to withstand the side blows to which it is exposed (particularly if used as a leading centre) when the miners are blasting rock or other material in the forward length. The extent of the repairs at Blechingley was considerble, not only arising from this cause, but, being taken so completely to pieces each time they were shifted, they were more liable to injury, particularly in the scarf joint; whereas the segment centre is not so completely taken to pieces, for each of its two segments will pass through an opening 5 feet 6 inches in width.

SETTING AND SHIFTING THE CENTRES.

As the bricklayers bring up the side walls, they leave holes about 13 inches deep (*a*, figs. 1 & 2, Plate IX.) at the proper places, for the reception of the ends of the sills; *a* in fig. 2 shows the hole from whence a sill has been

removed forward. When the walls are at their full height, the sills, which are in two parts, scarfed together in the middle, as shown at A, fig. 1, are set in their places, and joined together at the scarf; the plates are then bolted and the glands secured. Fig. 1 shows the sills, A, stretching across the tunnel, carrying the centres; and they likewise are shown in section at A A A, fig. 2. Each sill has two props, B B, under it: the bottoms of the props are wedged on the invert, and their tops fit into a collar spiked to the under side of the sill, as shown at fig. 5, where A is the sill, B the prop, and *e* the collar; the first and third figures are an end and side view, and the middle figure is a plan of the under side of the sill, showing the prop, B, nearly surrounded with the collar, *e*. The half-timbers, C C, &c. were next laid on the sills nearly at right angles thereto: by comparing figs. 1 and 2, their situation and arrangement under the centres will be obvious. Each half-timber was propped in the middle, or immediately under where the centre ribs take their bearing upon the half-timber, as shown at D D, &c. Instead of sills to support the centre, sometimes trestles are used; but at Blechingley the sills were adopted as the most preferable mode.

The centres were next put together across the half-timbers, and, when set up in their required places, were raised to the proper level by the slack blocks or wedges, E E, &c. and also at large in fig. 6, where the wedges are shown both in a side and end view. Upon the centres the laggins were laid, and thereon the arch turned.

It may be well here to call attention to the oblique manner in which the half-timbers are placed, as represented in the engraving; one end of each of the middle half-timbers and the slack blocks are under the heel of the leading rib, as at *b b* (fig. 1); whilst the other end of the same half-timbers is under the queen post of the scarf centre, as at *c c*, and, as the queen posts in that kind of centre are nearer the centre of the tunnel than the heel of the segment, or leading centre, such oblique position of the half-timbers is necessary to take those important bearings of the two ribs.

The setting of the three centre ribs, as above described, is all that is required for each of the side lengths, where they ought to remain after the arch is turned during the time that the shaft length is completed, and also the

first leading length each way, when the one nearest the shaft will be taken forwards without disturbing the other two. By referring to Plate IV. fig. 1—where the side lengths are shown as complete, and the excavation for the shaft length ready for the brickwork—it will be observed that each side length has all its three centre ribs remaining under it, and by referring to Plate V. fig. 1, the same shaft length is represented as complete: in this case it will be seen that each of the side lengths still has its three centre ribs undisturbed, and that the arch of the shaft length has been turned upon four additional centre ribs, two of which will be carried each way for the leading lengths, to make up the five centres required on each side of the shaft, as described at page 143.

Upon the completion of the shaft length, the centres and laggings were removed from under it, and a leading length on one side commenced; and as soon as the side walls were up springing high, the centres were set without disturbing those in the side length, except the back one of all (nearest the shaft) which was brought forward. Fig. 1, Plate IX. is a cross section of the tunnel, showing the work in this state, and fig. 2 is a longitudinal section of the same, the cross section being taken near the face of the excavation through the line, F G, looking towards the completed portion of the tunnel. The brickwork is shown as being above springing high, and part of the arch turned, as at H H, six of the laggins on each side having been already laid on the centres.

Figure 2 shows the five centre ribs in use at one time: three under the length in progress, and two supporting the laggins under the last turned length, the third or back rib having been moved forward for use under the advanced work. When the arch is completed the whole five ribs remain unmoved under the two lengths (as shown in fig. 2), during the whole of the time another length forward is excavated, and also until the invert and side walls of the same are constructed, thereby materially assisting the new brickwork to sustain whatever pressure it may have to bear, not only from the earth above itself, but one-half the weight of the newly excavated length, as may be seen in fig. 2, where the brickwork, K, has to carry half the weight of the new length, because one end of all the bars rest upon it near its end, as at L.

Furthermore the invert and side walls, being constructed before any of the centre ribs are removed, they form a buttress against the completed work that prevents any tendency in those lengths to slide forward and separate from the preceding work; for it sometimes happens that nearly a whole length will move onward, and leave an open joint between itself and the length it had separated from; for in all these operations the work has a tendency, as before stated, to press forward in the direction in which it is carried on. None of the supports of the arch of the two preceding lengths were ever disturbed at Blechingley Tunnel till wanted for a third length; for although the back rib of all was moved forward, as in fig. 2, yet the laggins of the said back length were kept tight up to the arch by the remaining two ribs, so that two lengths of 12 feet each, or 24 feet of completed work, remained with its full support, not only till the next length was excavated, but until the next side walls were up ready for the centres.

Under these conditions every length was well able to bear the superincumbent weight until it received assistance from the neighbouring advancing length, the construction of which to the springing height necessarily occupied some days, and therefore the cement had time to harden before the weight came upon the arch after the removal of the centre ribs, which is an important advantage.

But when, from motives of economy, three ribs and one set of laggins only are used, the whole support must be removed from under the first length before a second one can be turned, and again must be in like manner removed from the second before the third can be constructed, leaving the back work without support; which occasionally causes it to give way, the bricks to crush, and frequently the last two lengths to be separated from each other; and if the arch does not come in, it is often bulged in various directions, and consequently unsightly if not unsafe. Enough has now been stated to show that, in heavy ground, at least, the cheapest method of proceeding is not the best, or, at all events, not the safest.

FRAZER'S PATENT CENTRES—PLATES X. AND XI.

A set of Mr. Frazer's centres consists of three ribs, which are represented as in use in Plates X. and XI. In fig. 1, Plate X. which is a transverse section of Saltwood Tunnel, they appear, as viewed from the face of an advanced or leading length, when such length is completely excavated and timbered ready for the bricklayers to commence the construction of the invert. The centres are in the position they held when the arch of the last length of brickwork was turned, and therefore they appear to be supporting the said arch. Fig. 2 is a longitudinal section of a portion of the tunnel, showing the same state of the work, and consequently at a time when the centres are at rest, waiting to be advanced onward as soon as the invert of the next length and the side walls thereof, up to the height of the springing of the arch, are constructed. Fig. 1, Plate XI. is also a longitudinal section, showing the invert and side walls, and the centres advanced and adjusted to their places, ready for the bricklayers to commence upon the arch.

The three ribs are distinguished in the following description by the letters A, B, and C—A being the leading rib, B the middle rib, and C the back rib. Each rib is constructed of elm timber, 4½ inches in thickness, and 16 inches wide, and consists of four pieces scarfed together, as shown in figures 1 and 4, Plate X. In the ordinary construction of centres, the ribs when the laggins are upon them are all of one size, and of the same span and rise as the under side (or soffit) of the intended arch; but in Mr. Frazer's centres all the three ribs differ from each other in dimensions of their radii, and the middle rib is the only one that acts in the same way as centres of ordinary character, namely, having the laggins and the arch immediately resting upon the rib, and consequently, with the laggins, is of the same dimensions as the arch (in the clear). The leading rib is larger, and the back rib smaller, than the said dimensions. Each rib will now be described separately.

The leading rib, A, is 12½ inches larger radius to its outer edge than the under side of the arch, and 3½ inches less radius to its inner edge; both edges are covered with half-inch iron plate, bolted quite through the rib (see

fig. 4), where the plates are shown at *a a*, and the bolts at *b b*, &c.; the plate on the under side is 6 inches wide, and is placed to project 2 inches over one side of the wood, forming a flange for the laggins (which are 3 inches thick) to rest upon, as shown in section, figs. 2 and 5; the former being a longitudinal section taken along the centre of the tunnel, shows the *keying-in* laggins, resting upon the flange, and the latter shows the *long* laggins so resting, wherein A is the rib, *d* the iron plate projecting over the rib, inwards, upon which projection the laggins, *e*, rest.

When the laggins are in their places their upper surface forms the core or bed upon which the arch is to be constructed. The leading rib, when set, must be its whole thickness in advance of the end of the intended length of brickwork, and therefore it will stand in front of, or cover 12½ inches of the toothing end of the same; this forms a convenient mould to guide the toothings of the work as they are brought up, the same being set out, and chocks of wood being nailed thereon, compels the bricklayers to keep their work regular. The chocks are shown at *c c c*, &c. fig. 4, which figure shows the inner face of the rib.

The ribs, B and C, rest upon and are fixed to a trestle, D, on each side of the tunnel; but it will be seen, figs. 1 and 4, Plate X. and fig. 2, Plate XI. that the leading rib, A, is supported by wedges or slack blocks, *d*, upon the end of the brickwork of the side walls, E, which for this purpose is carried up 9 inches longer than the arch of the said length is intended to be. This, Mr. Frazer states, was all the support that he ever found necessary to carry the said rib and its superincumbent weight; but at Saltwood Tunnel, where the ground was heavy, and the bricks none of the best quality, the weight pressing upon the said rib occasionally broke off the end of the brickwork upon which it rested; in cases, however, where all circumstances are favourable, the plan of resting the rib upon the end of the brickwork may perhaps be sufficient, but it would certainly appear to be by no means a safe method of proceeding without the support of the props, F, which will next be described.

This prop is represented at F, figs. 1 and 2, Plate X. and at large figs. 2 and 3, Plate XI.; the upper part of the two latter figures shows two views of

the top of the said prop supporting the rib, A, and the lower part shows the manner in which the prop is supported upon the invert, part of the skewback of the invert being cut away to receive an iron block, G, for the square end of a capstan-headed screw-bolt, *f*, to rest upon, the screw of the said bolt being the means of tightening up the prop when set in its place under the rib; the foot of the rib is held between two iron cheeks, *g g*, which are fastened to the top of the prop by a bolt, *h*, and a collar, *i*, figs. 2 and 3, plate XI. The end of the upper slack block passes between the iron cheeks, and appears at *k*, figs. 2 and 3, thus affording facilities for striking the same when the rib is to be eased; the under slack block does not extend within the iron cheeks, but is cut off at about the level of the brickwork, as at *l*, fig. 2.

Before the prop can be applied to the rib to assist the brickwork in carrying it, the rib must first be set and tightened up, or adjusted in its place, ready for the reception of the laggins and the brickwork; such adjustment being effected by driving or easing the slack block or wedges, because the prop is in the way of any alteration of the said wedges, after it is fixed and tightened up to the heel of the rib, by the screw *f*, at the bottom of the prop.

The middle rib, B (and also the back rib, C), stand upon, and are permanently fixed by brackets and straps and bolts to the trestles, D, as shown at figs. 6 and 7, plate X. and moves forward with it upon the rollers, *m*, figs. 1, 2, plate X. and 1, plate XI.; the under side of the middle rib is covered with half-inch plate iron in one piece, bolted through, as shown in fig. 7, plate X. which gives strength to the arched rib in the same manner as the struts, &c. apply in centres of the ordinary construction. The bolt and nut are shown at large, fig. 9. The laggins, *e e*, &c. rest flat upon the upper edge of the middle rib, and therefore the radius of this rib must be the same as of the arch, all but 3 inches (the thickness of the intervening laggins), and, as before observed, it is the only rib of the three that carries its load like the centres of the common kind.

The back rib, C, is also strengthened with a covering of half-inch iron in one piece on its under side, bolted through like the middle rib, with this difference, that patent screws, fig. 12, are substituted for every alternate bolt, as they are cheaper than the bolts: between each bolt and screw a hole is

made quite through the rib, to receive the stem of a bearing iron, *n n*, &c. fig. 6, and at large, fig. 10; and there are as many bearing irons as there are to be laggins. It will be seen, fig. 6, that the laggins do not rest upon the back rib itself, but upon the bearing irons, which project from the timber or upper edge of the rib, the amount of projection being regulated as may be required to press the laggins to their proper level, by means of adjusting screws, *o o*, &c. which are tapped into the half-inch iron plate, and act upon the stems of the bearing irons; and, conversely, the reversing of the said screws lowers the bearing irons and eases the laggins from under the brick-work, one by one, to be removed forward.

As before stated, the ribs, B and C, are permanently fixed at their footings to the trestles, D, and they are also steadied at their crown by the irons, H H, as shown in fig. 2, Plate X. and fig. 1, Plate XI. These irons are movable at one end, which, forming a hook, drops into an eye screwed into the side of the rib; the bricklayers, by unhooking either of the irons, can put them out of their way when the work advances towards the crown of the arch; each iron, however, can only be unhooked at one end, the other end being permanently fastened by the eye to the other rib, so that, when unhooked by the workmen, they hang down as shown at H′, fig. 2, Plate X. If they were not so attached to the ribs they would very soon be mislaid and lost.

The trestles, D, with their load, move upon rollers, *m*, and half-timbers, I I, figs. 1 and 2, Plate X. and fig. 1, Plate XI. laid longitudinally, as a kind of tramway for the rollers to run upon; the half-timbers are held in their places on the skewback of the invert by bricks or blocks let therein for that purpose.

SETTING AND SHIFTING THE CENTRES.

In setting these centres for the turning of the arch, the leading rib must first be set in its place, and wedged up, on the end of the brickwork, E, until it is at the correct level; the prop, F, is then to be placed, and screwed up tight under the heel of the centre, which will readily be understood by those who have attended to the previous description; next, the trestles, D, are

rolled forwards, until the ribs, B and C, are advanced to their proper places; when this is done, three pairs of wedges and blocks, K K K, are placed between each trestle and the half-timbers, and by their use the trestles are lifted up, until the top of the middle rib is upon a level with the iron flange of the rib, A, thus forming two level bearings for the laggins; next, the bearing irons of the ribs, C, must be pressed outwards by the adjusting screws, *o o*, until the top of each of them is also upon the same level; so that, when the laggins are placed one by one upon the three ribs, they will bed solidly upon them all; the adjustment of the bearing irons or of the three ribs may be tested by passing a laggin over each of the irons and the other two ribs in succession, for the first length of the brickwork; but in all succeeding work their adjustment is regulated by the brickwork last completed, as will be shown presently. The three bearings of each laggin, when the ribs are adjusted for the in tende arch, is as follows:—1st, *upon the iron flange of the leading rib*, 2ndly, *upon the middle rib itself*, and 3rdly, *upon the bearing iron of the back rib*; when this is all made correct, the centres will be ready for the bricklayers to turn the arch, and by whom the laggins are laid on one by one as the work advances.

When the arch is completed the miners again take to the work and excavate and timber another length, as shown at fig. 2, plate X.; as soon as this is done the bricklayers re-enter and construct the invert and side walls to the springing height; the centres have then to be advanced for turning the arch. Fig. 1, plate XI. shows this stage of the work; the side walls are represented as up, and the centres in their places; four laggins are also shown as drawn forward, and the work of the arch commenced. The detail of the method of moving forward the centres now remains to be given.

First a rib, called a jack rib, L, is fixed under the laggins, in the rear of the back rib, C, fig. 2, plate X.; this jack rib consists of an iron plate, 1 inch in thickness and about $2\frac{1}{2}$ inches wide, which is bent into a form of the arch of the tunnel. Fig. 8, plate X. shows a portion of the jack rib upon a larger scale, wherein it will be seen that, opposite to every alternate joint of the laggins, a screw is tapped into and passes through the rib; which screws have their outer end finished as a loop, whereby they may be turned with a

lever; their inner ends are finished with a square head driven on to the end of the screw, and are similar in appearance to the ends of the bearing irons of the back rib, C, before described, but not so stout, neither do they revolve as the screw is turned round.

The screws being placed opposite every alternate joint of the laggins, it is clear that only half the number of screws that there are laggins are required, as each screw presses against two of them at a time, and exerts quite sufficient force to retain the laggins in their places when the ribs, B and C, are removed from under them; and which is all that is required of the jack rib. This arrangement is fully shown at fig. 8. *r r*, &c. are the screws passing through the iron plate, *s*, that forms the rib, the square end of each screw pressing two laggins, *e e*, &c. at their joints, against the brickwork of the arch, M. The jack rib terminates with a screw, O, which works in sockets, as shown in the figure, and its extremity rests upon an iron bar, N, about 2 feet long and 4 inches wide, driven temporarily into the brickwork, for the purpose of carrying the rib.

The jack rib will be understood to be only a flat iron arch, springing from the iron support, N, on each side; and its use is simply to support the back ends of the laggins by means of its screws, *r r*, &c. when the trestles, D, with the two ribs, B and C, are removed from under them by lowering of the wedges, K. The other ends of the laggins are at the same time supported by the leading rib, A, independently of the trestles, and therefore, under such circumstances, the laggins will continue undisturbed. They would, however, no longer be of use in preventing the arch above them from giving way, if it should be subjected to extraordinary pressure before the cement is well hardened, the leading rib being the only part of the centering that would afford assistance in such a case. The use of the screw, O, fig. 8, is for the adjustment of the jack rib to its required elevation under the arch, or the laggins.

As soon as the jack rib is fixed, and its screws, *r r*, &c. adjusted to take the ends of the laggins or press them against the brickwork of the arch, the iron bar, H′, is unhooked and left to hang down, as shown at fig. 2, Plate X. and the wedges, K K, &c. are eased, whereby the trestles are lowered, and

their rollers, *m m*, rest upon the wooden tramway laid for their reception, which tramway being then continued in the direction that the work is proceeding, the trestles are rolled onwards; and with them, of course, the middle and back ribs, B and C, which are thus advanced to their proper position for the turning of a new length of the arch. When the ribs, B and C, are lowered as above described, the middle rib, B, easily passes under the leading rib, A, which would yet remain in its place, under the toothing end of the last turned arch.

It will be remembered that the leading rib, A, was described as placed in front of the brickwork of the arch, its iron plate carrying the ends of the laggins; this arrangement, which is shown in section at figs. 2 and 5, Plate X. is contrived in order to keep as much clear headway as possible for the passing of the middle rib under it when that rib is advanced, with the trestles, to the next forward length.

The trestles, with the ribs, are moved forwards until the back rib, C, nearly abuts against the rear edge of the leading rib, A, or, more particularly, it is moved till it is within six inches of the ends of the laggins, when they are again wedged up to a proper level, as before; the bearing irons of the back rib, C, are then pressed by their screws home to the laggins of the arch, which afford them and the superincumbent brickwork the same support at that end that had hitherto been obtained from the leading rib, A; whereupon the said leading rib may be released, by easing the wedges, *d*, at its springing, and moved onwards by passing it over the rib, B; it is then to be fixed, as before, on the end of the brickwork of the newly-constructed side walls, and adjusted, together with the rib, B, to their proper level, which may be proved by ascertaining that the laggins of the arch already completed, *if produced*, would fit on the ribs, A B, in the same straight line. The props F, &c. must then be again fixed on each side, to support the heels of the rib, A.

When the centres are set, and adjusted to their proper level, as above described, they are ready to receive the brickwork of the arch; for which purpose the same set of laggins are again used, they being drawn forwards from their last place, one or two at a time, as they are wanted, beginning at

the springing. One of the screws of the jack rib, and the corresponding screw or bearing iron of the back rib, C, are eased, which releases the laggins against which they pressed, and admits of their being drawn forward to their places on the advanced centres; the screw of the bearing iron of the back rib is then again tightened, which presses the rear end of the laggin tight against the arch, or under the toothing end of the last turned length. The three bearings of each laggin, as it is so advanced and placed, will be, as in the former case (if the centres are correctly adjusted in position), *on the iron flange of the leading rib*, A, *on the middle rib itself, and on the bearing irons of the back rib.* Upon the laggins, as they are thus drawn forwards, the bricklayers construct the arch.

From the account above given, it will be obvious that (in using these centres) so soon as the arch of one length is completed, it remains supported by its centres and laggins, until another length is prepared by the miners, and the invert and side walls thereof are built; whereupon the two centres, B and C, are removed from under the said arch, leaving its toothing end only supported; for the jack rib does nothing more than keep the laggins from falling down. The back rib, C, is next brought under the toothing end, and its bearing irons screwed up tight to the laggins, which enables the leading rib, A, to be released and carried forwards; so that, from the time that the side walls of a second length are constructed, the last turned arch receives no support, except under its toothing ends.

Where the ground is heavy the use of a single set of materials of the ordinary construction has been explained, in the preceding pages, as being an unsound mode of proceeding; but this is by no means the case where the ground is light, for then one set of centres will be sufficient.

The patent centres, when used in heavy ground, do not afford anything like the support to the brickwork that is derived from the use of a double set of those of the ordinary construction. For ground that is light the patent centres are well adapted; and even when the ground is moderately heavy they may be advantageously employed, for they afford more security to the work than a *single* set of the ordinary materials, although they fall much short in that particular of a *double* set.

The great advantages the patent centres appear to possess over centres of the ordinary construction is in the total absence of queen posts, and struts, &c. (which form the framework of the last-named centres); they therefore leave a large open space for the scaffolding and materials of the bricklayers, who can get at their work with greater facility by having so much more room than is afforded by the ordinary centres. Another advantage, and which, in tunnelling through rock where much blasting is necessary, is great, namely, that the débris from the explosion is less likely to disturb or injure these centres; whereas, with the other kind of centres, it is likely to do much mischief, and occasion considerable outlay in repairs.

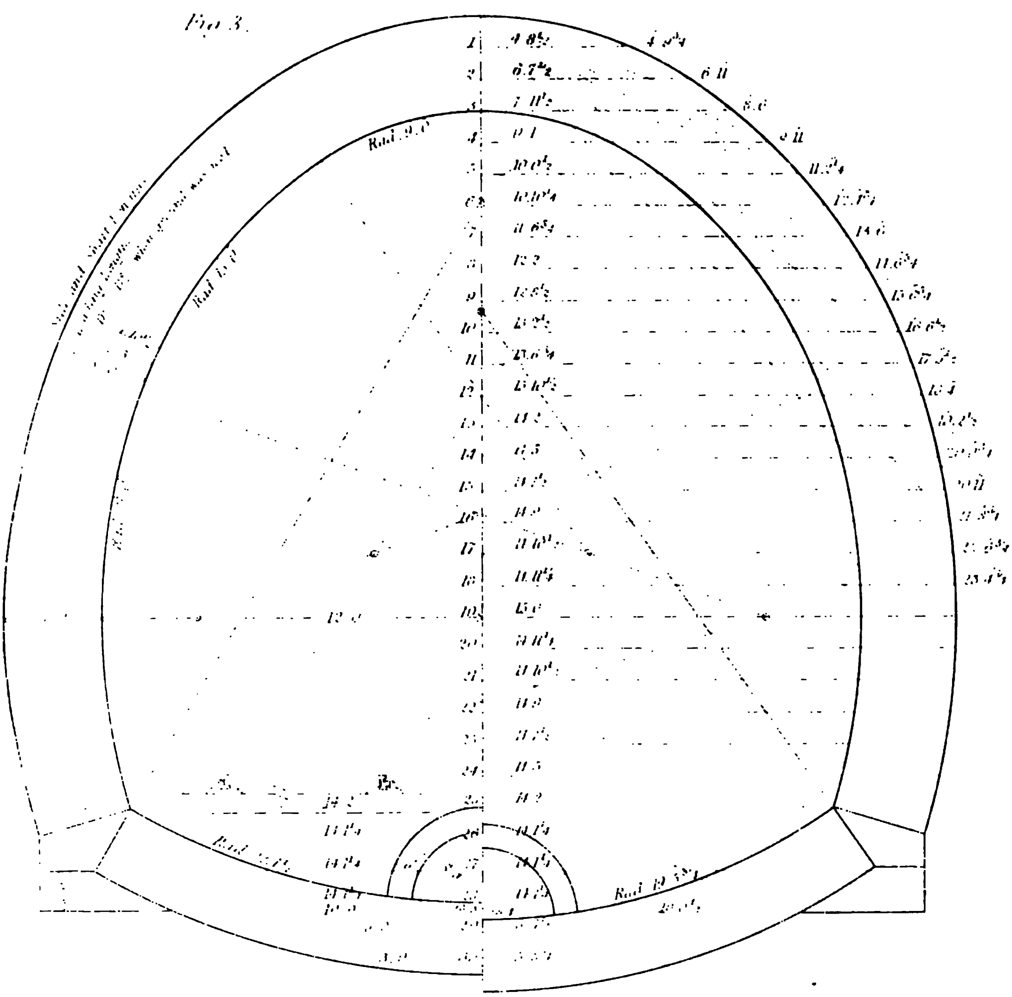
Independently of the difference in the first cost of the two kinds of centres, it does not appear to the author that any money is saved in the subsequent use of the patent centres; both kinds being equal in this respect.

Although it would appear, from the above statement, that a set of the patent centres, and necessary materials, are rather more expensive in their first cost than a single set of centres and materials of the ordinary construction, yet there can be no doubt that they are greatly superior thereto in their practical application; for although one set of centres and materials will be sufficient for tunnel works in light ground, yet there is no ground so perfectly homogeneous in character throughout a hill, but in some parts, from faults or local disturbance of the beds, will prove heavier than other portions of the same strata. When this case occurs, and the patent centres are in use, no cause for alarm need be apprehended, there being sufficient provision therein to withstand the effects of moderately heavy ground. The difference of the original cost ought therefore not to be considered, as compared with the greater security obtained by the use of them.

It must, however, be understood that the author's strong recommendation of Mr. Fraser's centres is limited to *light* or *moderately heavy* ground; for where the earth is very heavy, the use of a double set of materials of the ordinary construction is greatly superior thereto. Under such circumstances the extra cost in the original outlay would be nothing in comparison with the superior advantages to the security of the work during its construction.

PLATE 1.

Transverse Sections



[Between pages 156 and 157.

The great advantages the patent centres appear to possess over centres of the ordinary construction is in the total absence of queen posts, and struts, &c. (which form the framework of the last-named centres); they therefore leave a large open space for the scaffolding and materials of the bricklayers, who can get at their work with greater facility by having so much more room than is afforded by the ordinary centres. Another advantage, and which, in tunnelling through rock where much blasting is necessary, is great, namely, that the débris from the explosion is less likely to disturb or injure these centres; whereas, with the other kind of centres, it is likely to do much mischief, and occasion considerable outlay in repairs.

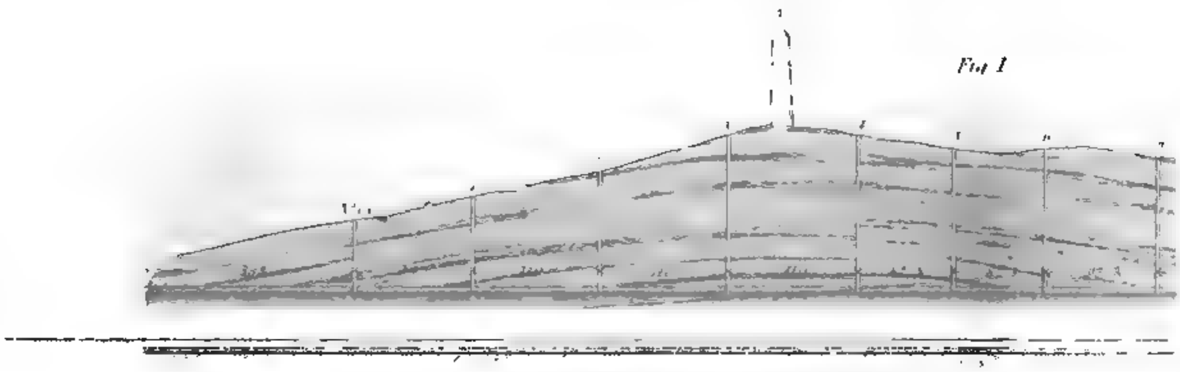
Independently of the difference in the first cost of the two kinds of centres, it does not appear to the author that any money is saved in the subsequent use of the patent centres; both kinds being equal in this respect.

Although it would appear, from the above statement, that a set of the patent centres, and necessary materials, are rather more expensive in their first cost than a single set of centres and materials of the ordinary construction, yet there can be no doubt that they are greatly superior thereto in their practical application; for although one set of centres and materials will be sufficient for tunnel works in light ground, yet there is no ground so perfectly homogeneous in character throughout a hill, but in some parts, from faults or local disturbance of the beds, will prove heavier than other portions of the same strata. When this case occurs, and the patent centres are in use, no cause for alarm need be apprehended, there being sufficient provision therein to withstand the effects of moderately heavy ground. The difference of the original cost ought therefore not to be considered, as compared with the greater security obtained by the use of them.

It must, however, be understood that the author's strong recommendation of Mr. Fraser's centres is limited to *light* or *moderately heavy* ground; for where the earth is very heavy, the use of a double set of materials of the ordinary construction is greatly superior thereto. Under such circumstances the extra cost in the original outlay would be nothing in comparison with the superior advantages to the security of the work during its construction.

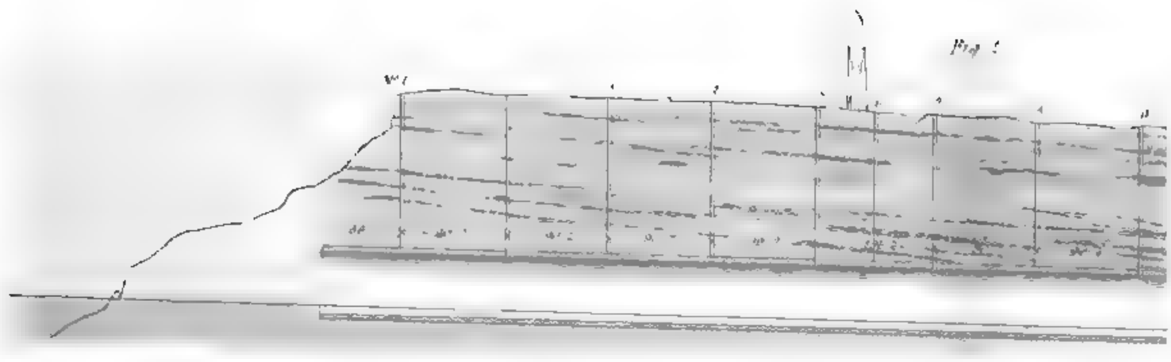
Longitudinal Sections

Fig 1



BLETCHINGLEY TUNNEL

Fig 2



SALTWOOD TUNNEL

I

SALTWOOD TUNNEL.

PLATE II

Working Shafts

Fig. 1

Transverse Section

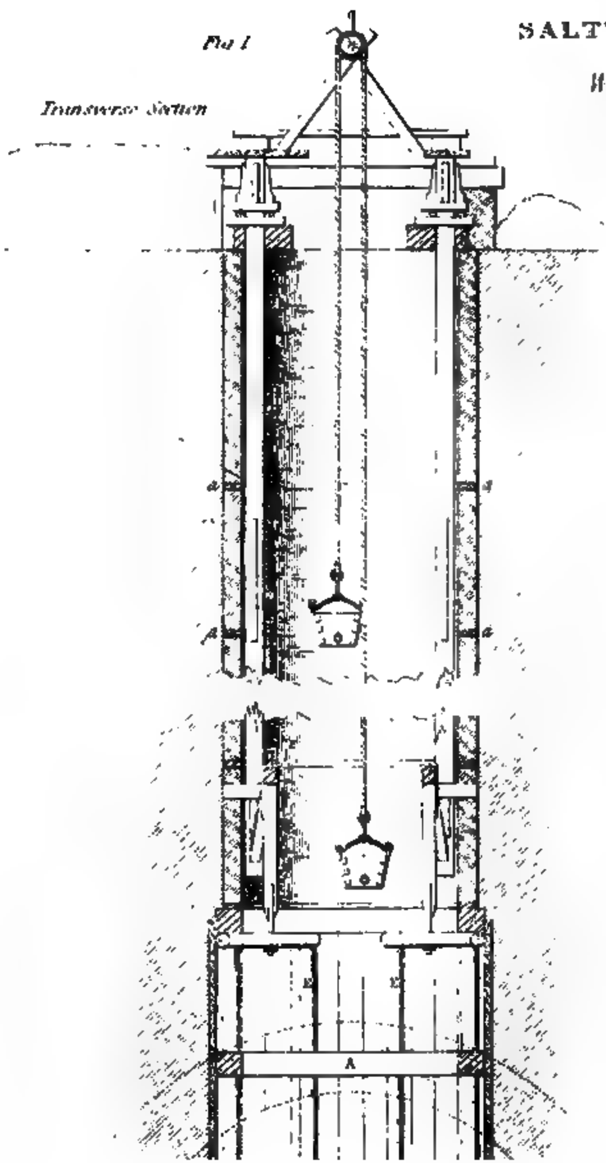
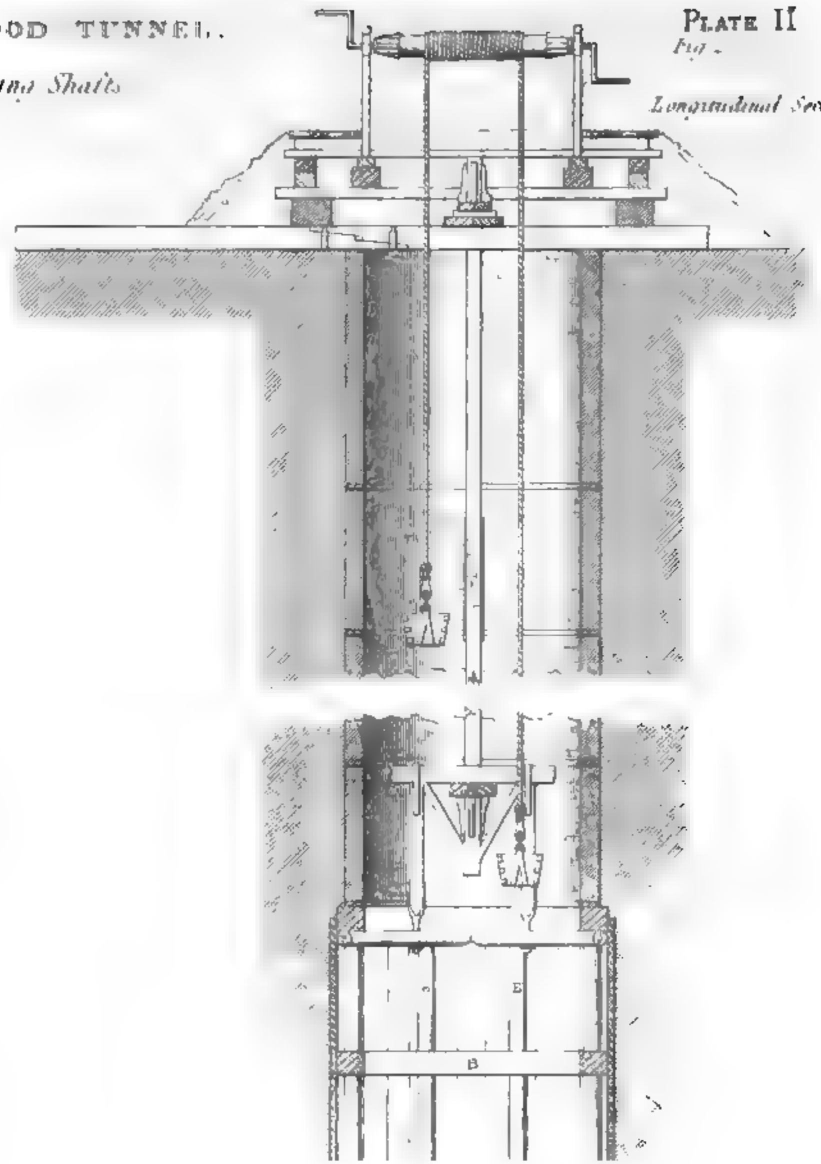


Fig. 2

Longitudinal Section.



SALTWOOD TUNNEL

Working Shafts.

PLATE II

Fig. 1

Transverse Section.

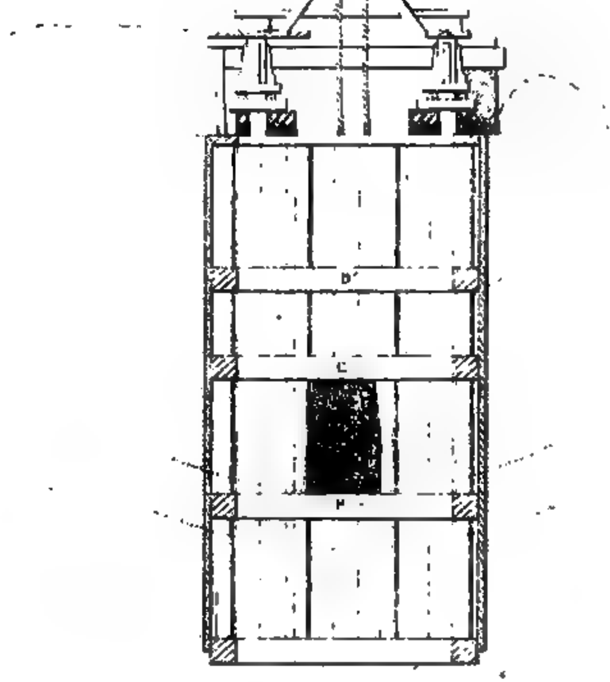


Fig. 2

Longitudinal Section.

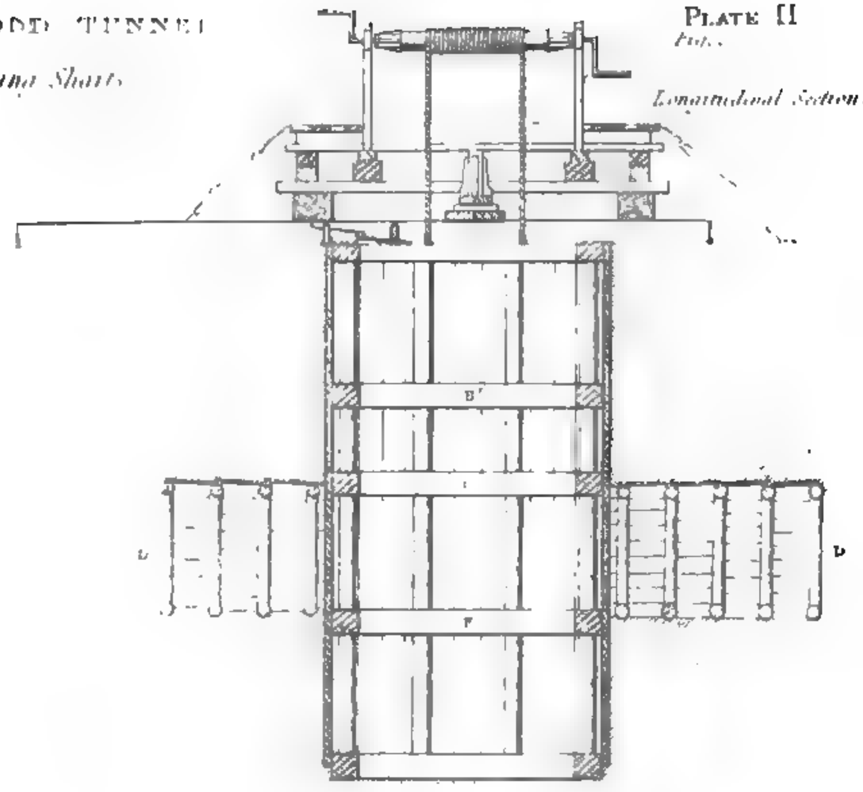


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Fig. 5.

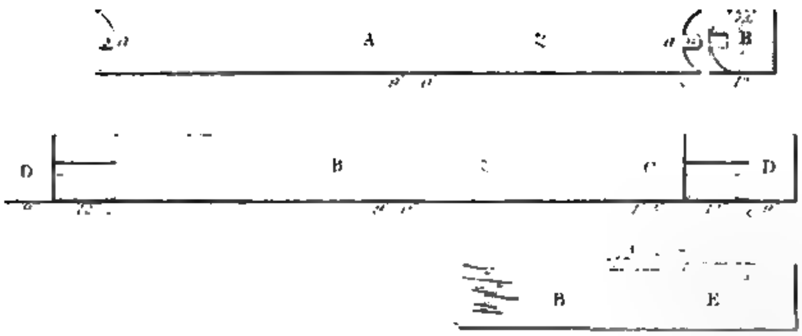


Fig. 6.

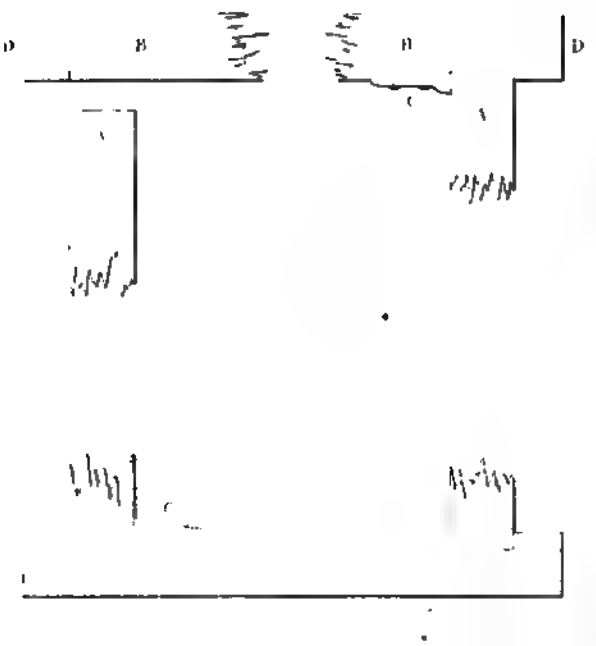


Fig. 3.

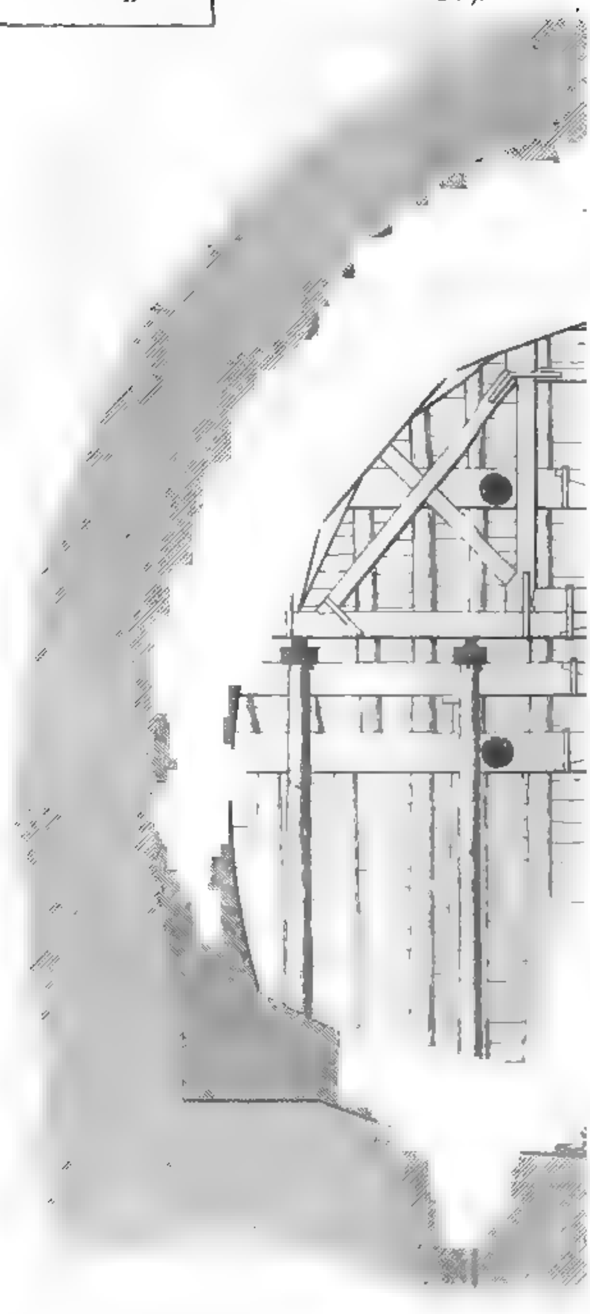
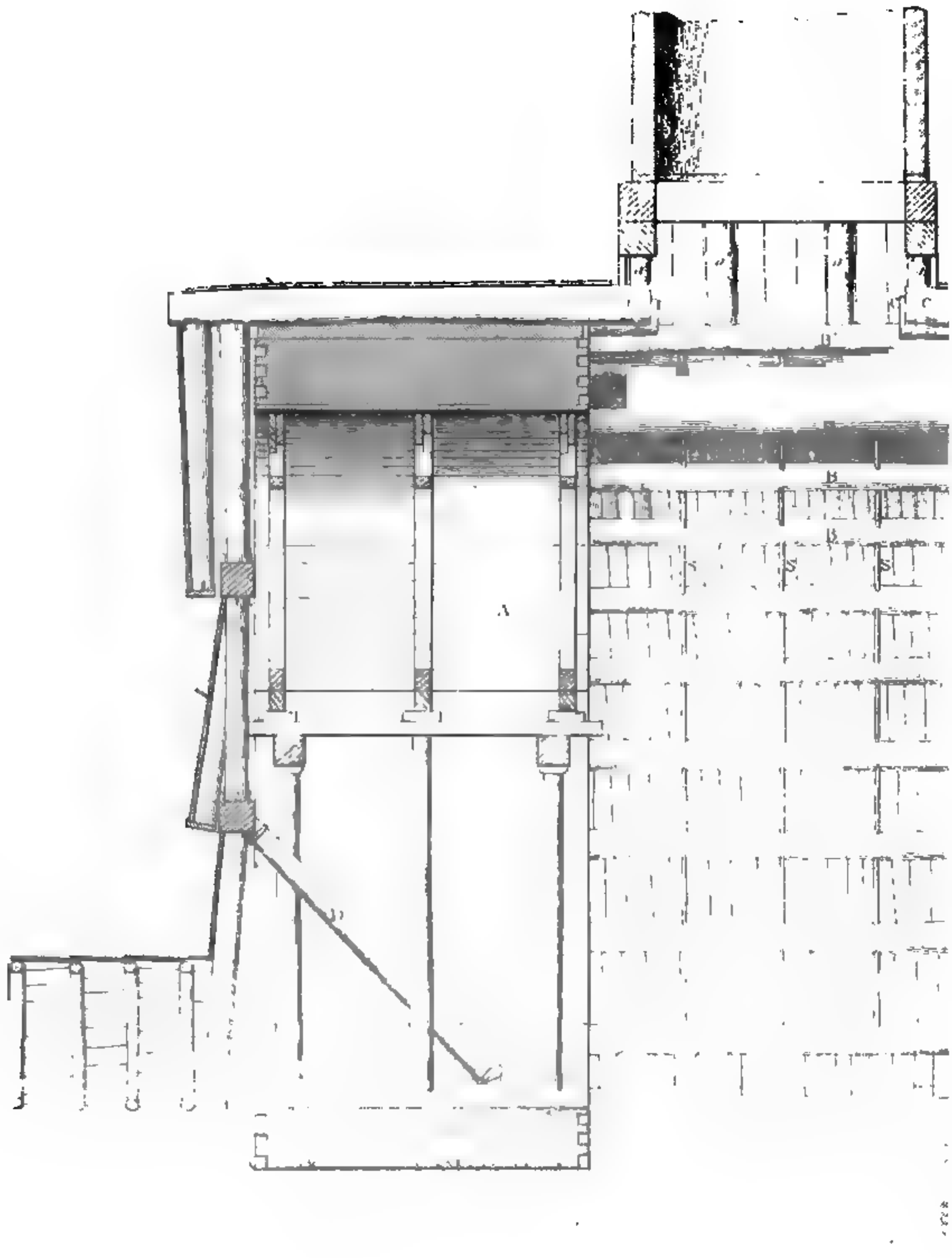


Fig. 1



BLECHINGLEY & SALTWOOD

SHAFT LENGTHS . BRICKWO

Fig. 1

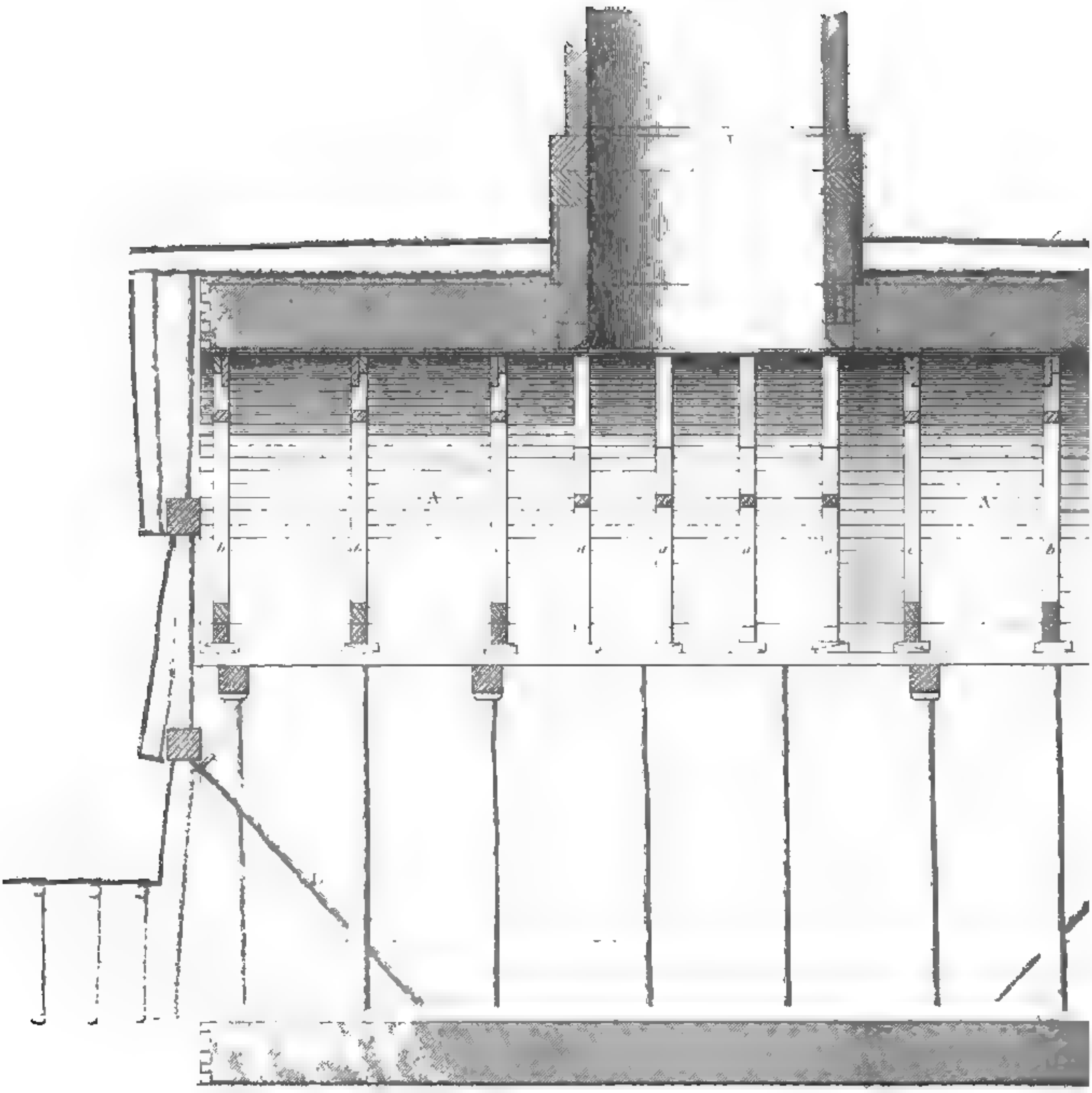


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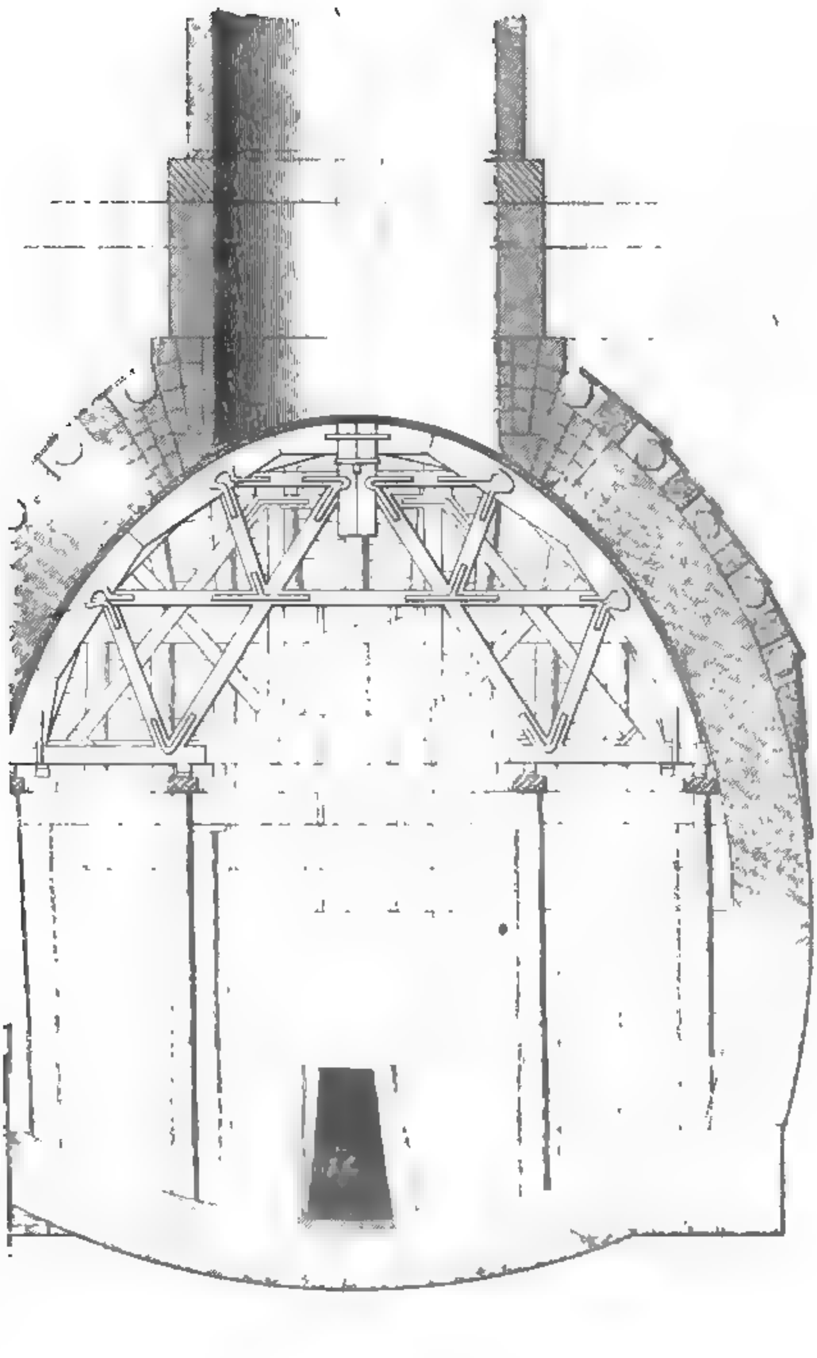
PLATE V

Fig. 2



Between pages 156 and 157

Fig 1

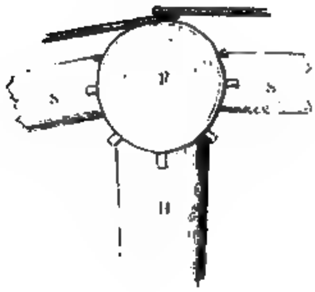
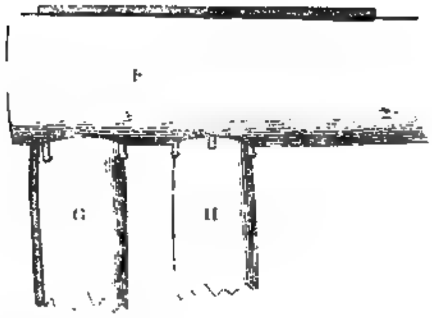
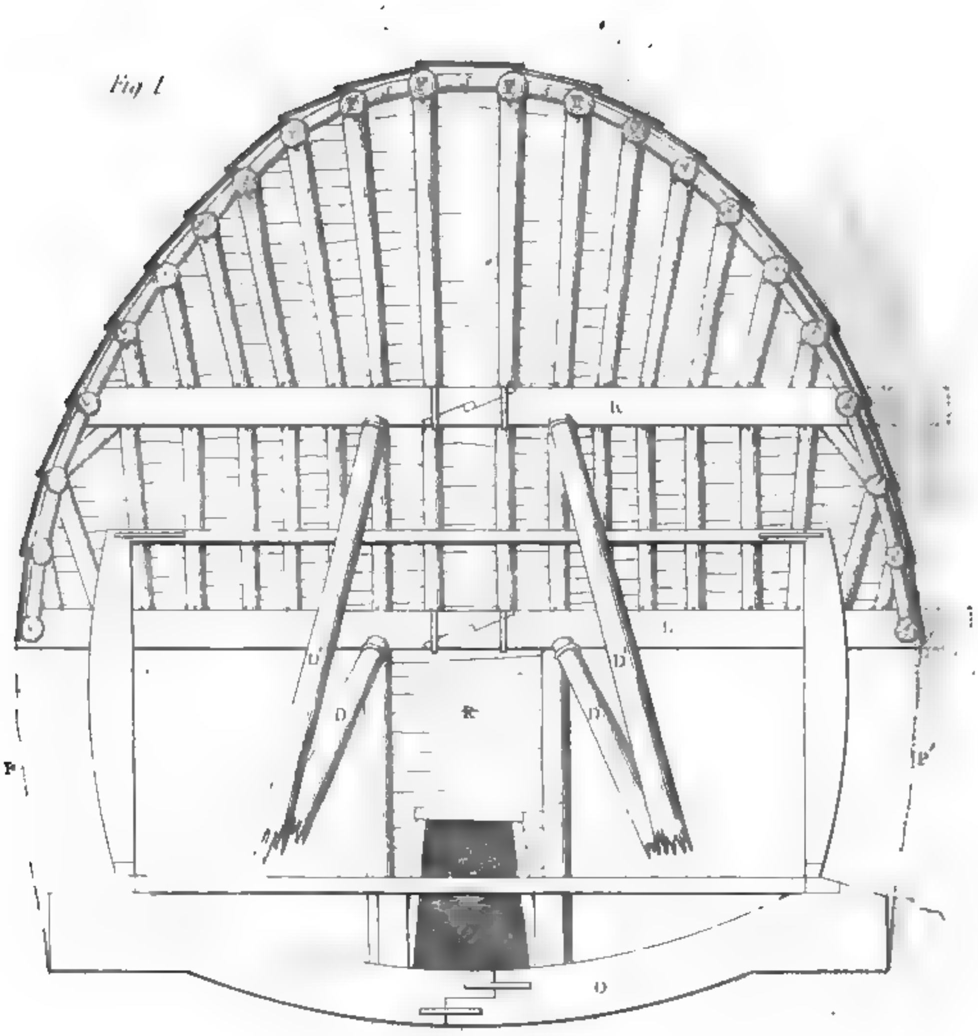


Fig 3



Section on line A B

Fig 2



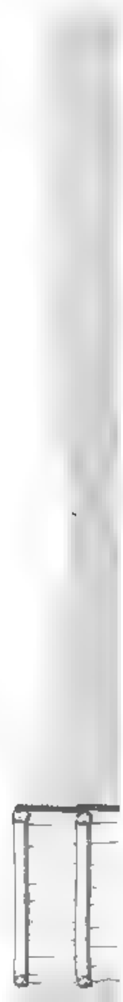


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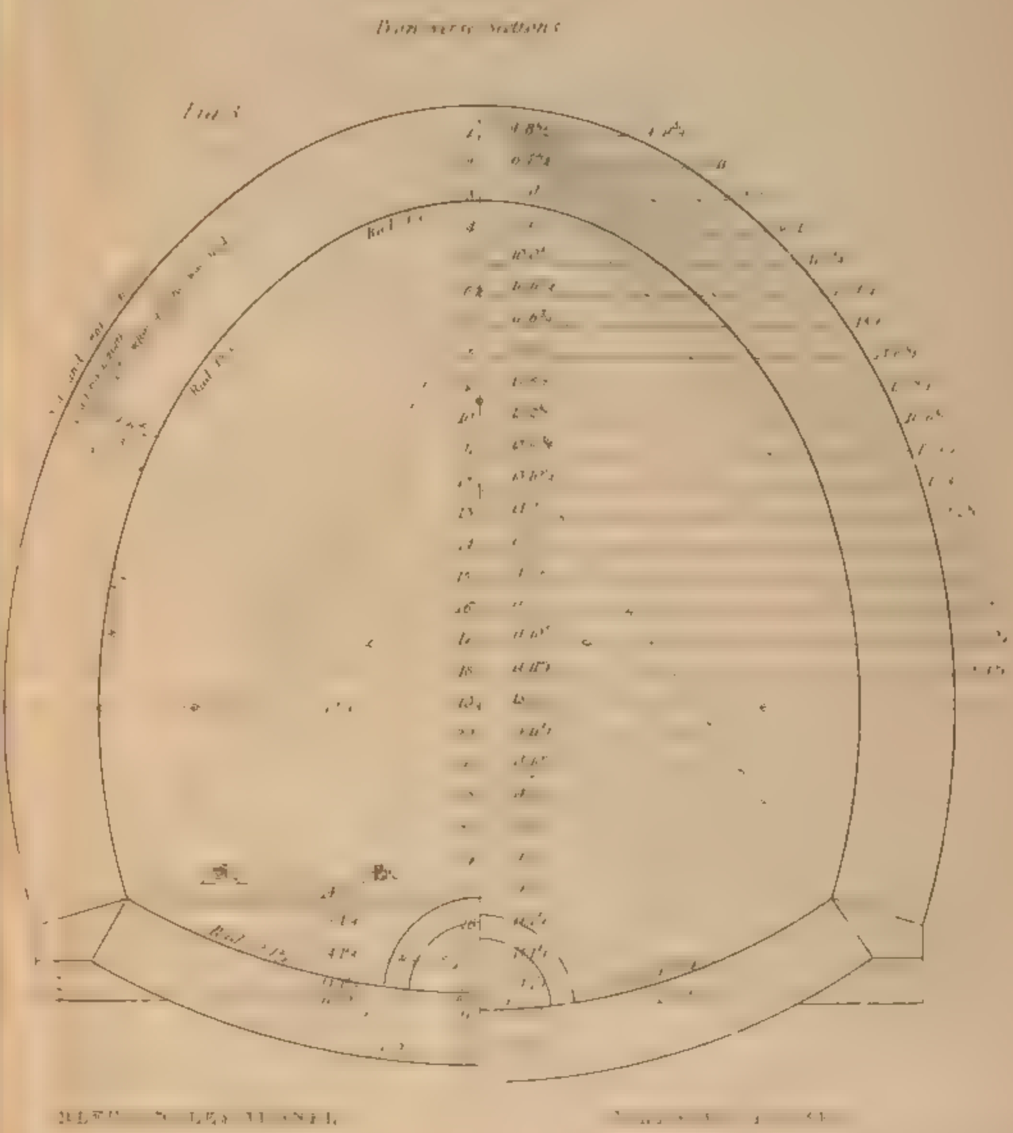
PLATE I



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BLECHINGLEY

LEADING LENGTHS

Fig. 3

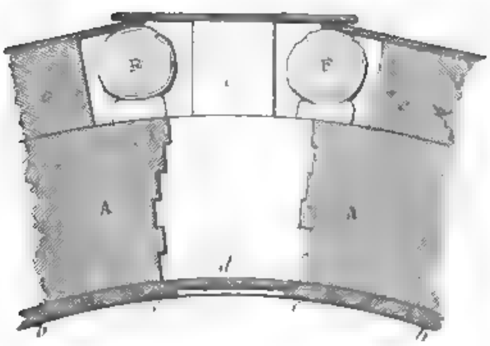

Fig. 1

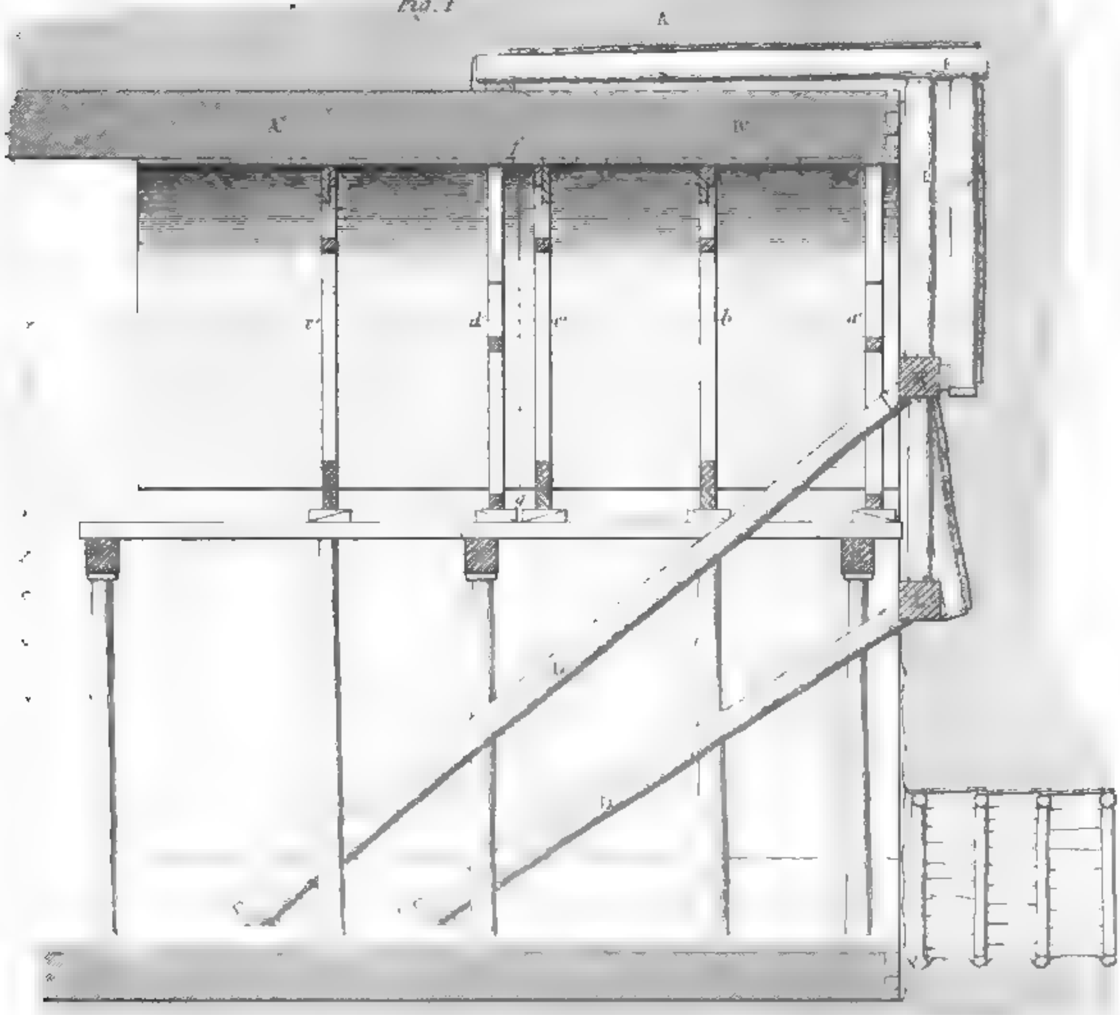

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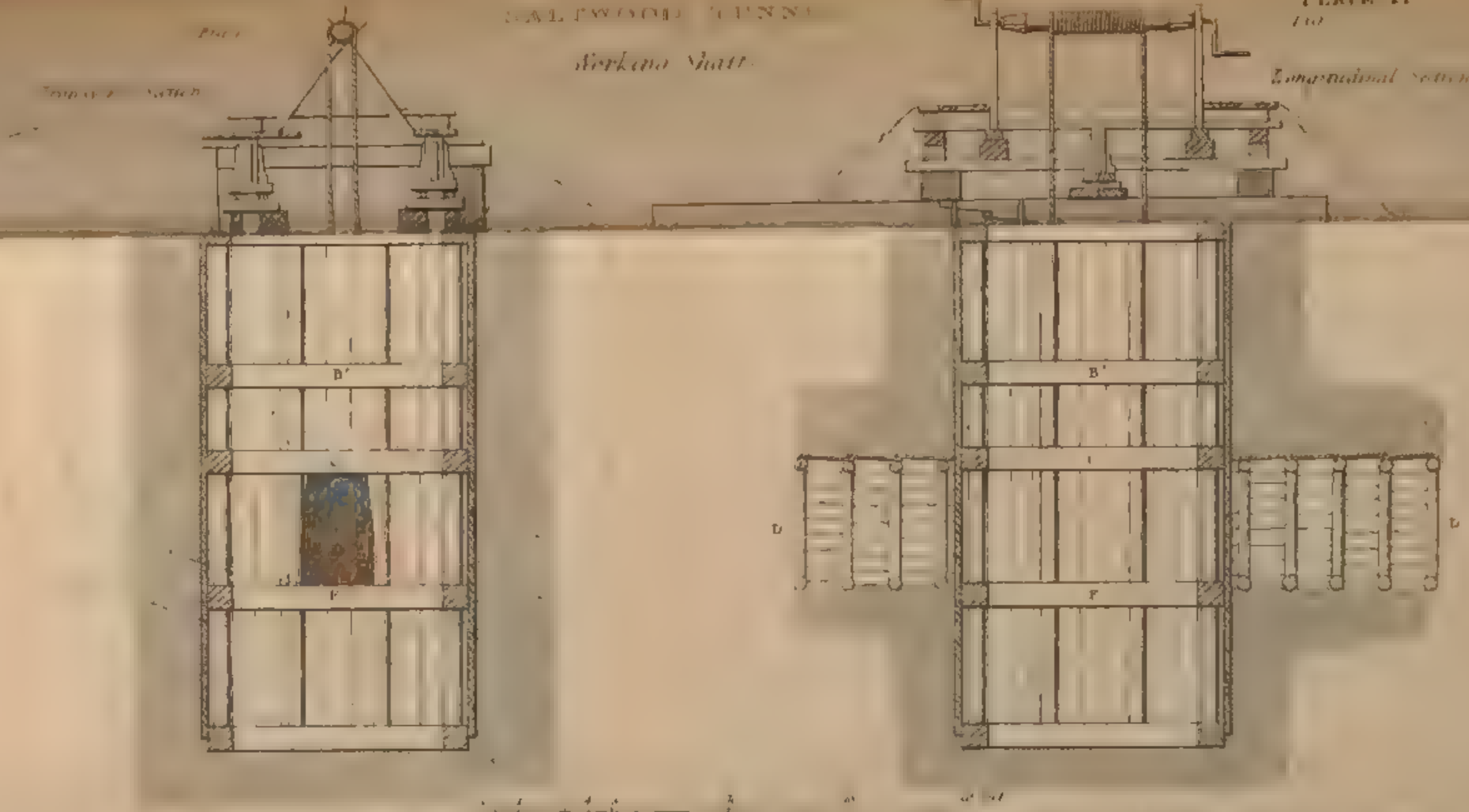
PLATE 11



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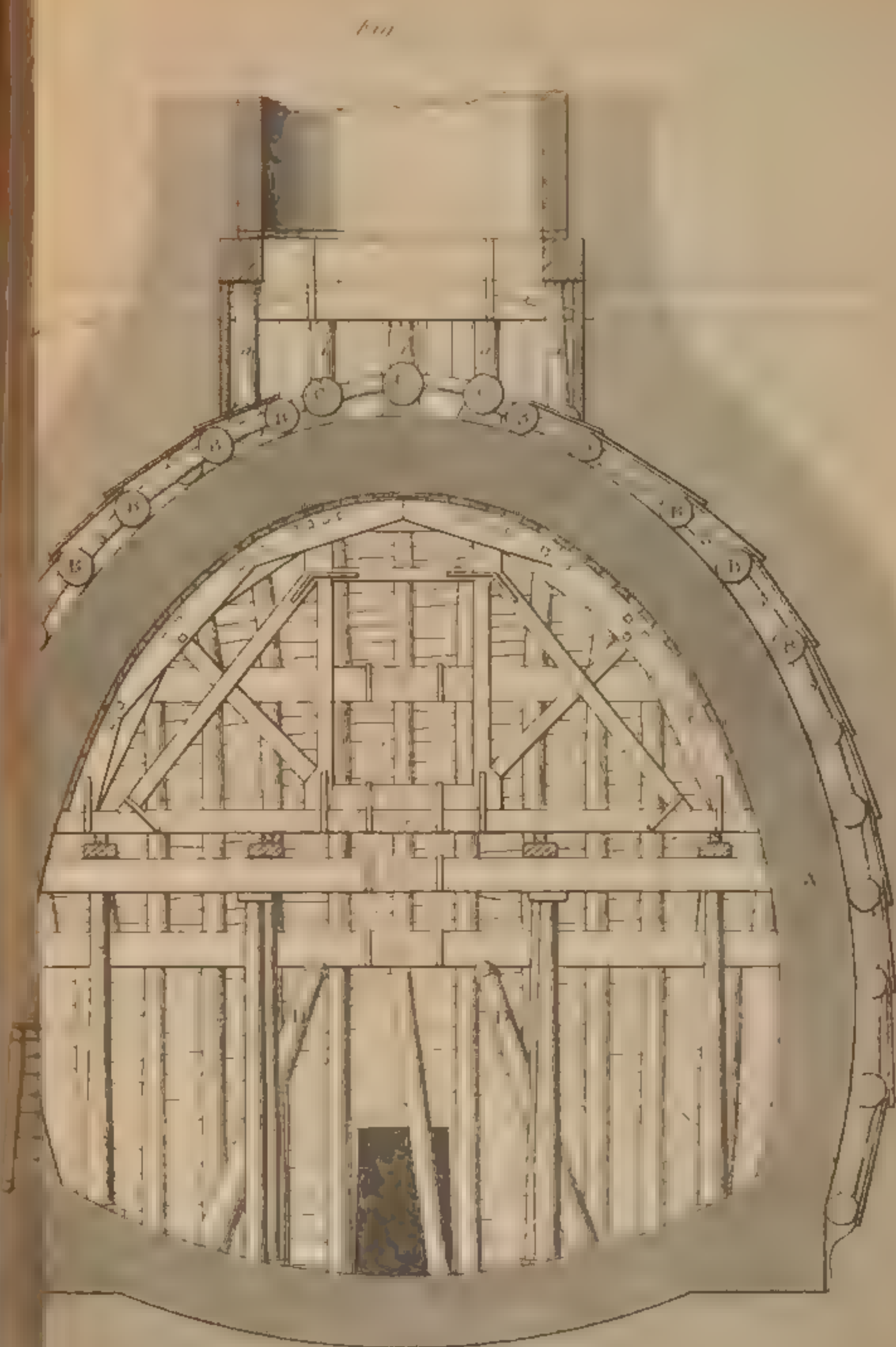
Between pages 156 and 157

PLATE IV



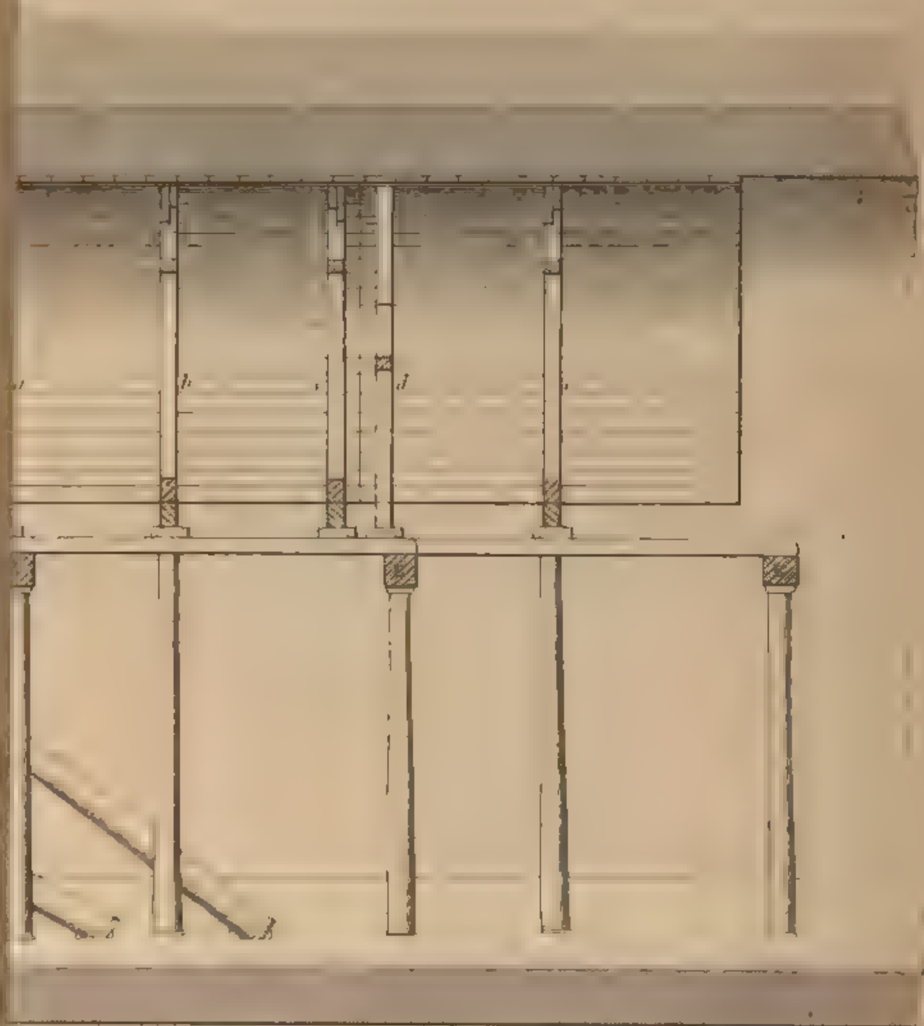
Between pages 156 and 157

Plate V

Between pages 156 and 157

PLATE VI

NGLEY TUNNEL.



Between pages 156 and 157

[Between pages 156 and 157

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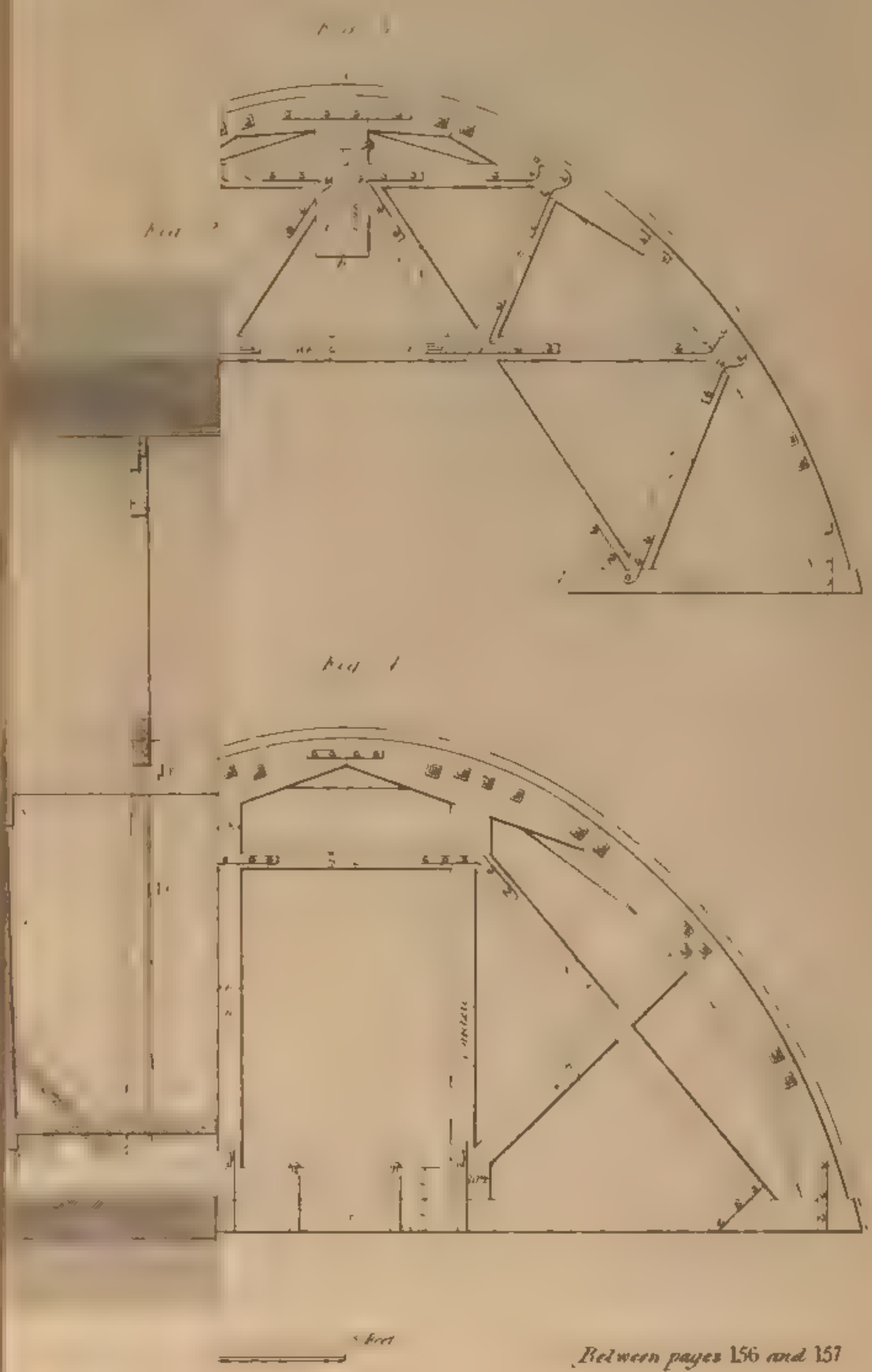
PLATE IX

NEL.



Between pages 156 and 157

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PLATE XI

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CHAPTER XIV.

LABOUR AND COST OF CONSTRUCTION.

THE cost of each portion of Blechingley Tunnel, the construction of which was entrusted to the Author, is given in detail, together with various particulars of the labour and the progress of the work. As the construction of the Saltwood Tunnel was let to contractors, the cost in detail cannot be given, as will be done in the case of Blechingley Tunnel, except for the preliminary works; but the total cost will be supplied, and, what will be at least as important, the amount or quantity of labour expended in the construction of various parts of the Tunnel will be given, and a comparison drawn between that and the corresponding labour at Blechingley.

COST OF THE TRIAL SHAFTS.

The price of the two trial shafts at Blechingley (page 52) was to be, for the sinking, eighteen shillings per yard down, and for the brickwork at the rate of sixteen pounds per rod, which prices were founded upon the estimate given in the following table:—

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ESTIMATED COST OF TRIAL SHAFTS AT BLECHINGLEY TUNNEL.

	£ s. d.	£ s. d.
EXCAVATION :—		
4·9 cubic yards in one yard down . at 2s. 6d.	0 12 3	
4 oak curbs for a depth of 33 yards, with plates and bolts complete £2 each, or per yard down . . .	0 4 10	
Props, chogs, spikes, nails, candles, &c. . .	0 1 0	
Excavation per yard down .	—	0 18 1
BRICKWORK, per rod :—		
Bricks . 4,500 . £2 2 0 per thousand Carting ditto . . 0 10 0 „ 2 12 0	11 14 0	
Lime . 1¼ yards at 13s.	0 16 3	
Sand . 3 yards at 2s. 6d. . . .	0 7 6	
Labour, candles, &c. . per cubic yard, 5s. .	2 16 7	
Per rod . . . . . =	15 14 4	
and ∴ per cubic yard . . . =	1 7 9	
and 1·8 cubic yards in one yard down . . . =		2 9 11
Total estimate per yard down . . . . . =		£3 8 0

From what has been stated of the unexpected irruptions of water, it is evident that the work could not have been done at the price at which it was undertaken, for in the estimated expense no such contingency as the occurrence of water was provided for, and, furthermore, the carting of the bricks to the ground cost 20*s.* per thousand, instead of 10*s.* as estimated; for none could be obtained nearer than seven miles, and by a hilly road. It justly fell upon the Company to pay these extra expenses, and the following will show the actual cost of these shafts:—

ACTUAL COST OF TRIAL SHAFTS AT BLECHINGLEY TUNNEL.

	£ *s.* *d.*	£ *s.* *d.*
Total outlay, 35½ yards done	202 17 2	
Deduct materials left for future work	20 15 3	
Total absolute cost	—	182 1 11
Estimated cost of 35½ yards	120 14 1	
Extra cost of carting 24,000 bricks, at 10*s.*	12 0 0	
		132 14 0
Extra cost upon the lower 15 ft. 6 in. of the western shaft, in consequence of water		£49 7 11

The men having taken to the work at a price per yard down, or running yard, reckoned at the rate of 2*s.* 6*d.* per cubic yard, it may be useful to show the amount of their earnings, thereby to judge how far the price was a fair one. The greater depth of the eastern shaft, where no difficulty occurred that was not anticipated, will give a fair average; for it must be remembered that great progress can be made at first, which necessarily diminishes as the shaft gets lower. On February 10th it was down 8 feet, and on the 26th, 59 feet—a difference of 17 yards in fourteen working days, averaging 1·2 yards per day—which, at 12*s.* 3*d.* per yard, amounted to 14*s.* 8*d.*

per day, to be divided among four men, and if we consider the odd 8*d.* to be the cost of the candles, it leaves 3*s.* 6*d.* per day for each man, supposing their earnings to be equally divided.

The cost of the trial shaft at Saltwood Tunnel (page 19) was as follows :—

COST OF TRIAL SHAFT AT SALTWOOD TUNNEL.

	£ s. d.	£ s. d.
CARPENTRY :—		
Large drum curb	5 5 0	
Smaller ditto	4 10 0	
Platform for workmen in the shaft. . . .	1 1 0	
Eight curbs or rims . 12*s*.	4 16 0	
		15 12 0
BRICKS : . 17,000 . at 51*s*.		43 7 0
Labour in excavating and bricking (or steining) 15*s*. per yard down		18 15 0
TOTAL		£77 14 0

COST OF THE WORKING SHAFTS.

Constructed according to the specification, page 68, the cost of the working shafts was as follows :—

COST OF THE WORKING SHAFTS PER YARD DOWN.

	At Blechingley, in the Weald Clay.	At Saltwood, in the Lower Greensand.
	£ s. d.	£ s. d.
EXCAVATION : Including all tools, gunpowder, candles and contingencies	1 10 0	1 2 0
BRICKWORK : Including all labour, candles, lowering materials and contingencies . . .	0 18 9	0 14 0
Bricks . 1,020	3 2 0	2 11 0
Lime . $\frac{1}{4}$ of a yard	0 4 3	0 4 3
Sand . $\frac{2}{3}$ of a yard	0 1 4	0 0 0
	£5 16 4	£4 11 3

In addition to the above, the cost of the ring curbs must be added, which at both places was the same, and averaged about one in every three yards down.

	£	s.	d.
Timber and workmanship	2	16	0
Ironwork—in plates, bolts, and nuts } 70lbs. . at 4*d*. .	1	3	4
	£3	19	4

The above details comprise the cost of the materials and the labour actually consumed in the work; besides which, there were the windlasses, ropes, hooks, skips, planks, and props, &c. which were part of the general plant of the tunnel works, but a very small portion of their cost ought justly to be charged to the shaft sinking; they are included in the total cost of the tunnels.

LABOUR AND COST OF THE EXCAVATION OF THE SIDE LENGTHS.

The following particulars show the amount of labour expended in the excavation of the side lengths, page 91, both at Blechingley and Saltwood:—

NUMBER OF MEN AND HORSES, AND THE NUMBER OF SHIFTS

Employed in the Excavation of the Side Lengths at Blechingley.

Number of Shaft.		Miners.	Labourers.	Horses.	Shifts.
1a	West	111	109	29	26
	East	93	100	22	21
1	West	122	109	28	25
	East	105	100	22	21
2	West	95	106	30	21
	East	66	90	20	15
3	West	122	127	42	29
	East	100	110	27	26
4	West	107	113	33	26
	East	103	96	33	24
5	West	85	80	22	18
	East	81	75	30	18
6	West	96	94	36	24
	East	84	76	27	19
7	West	109	100	30	27
	East	68	59	24	19

NUMBER OF MEN, HORSES, ETC. (CONTINUED).

Number of Shaft.		Miners.	Labourers.	Horses.	Shifts.
8	West	83	83	33	20
	East	65	67	27	15
9	West	94	93	24	20
	East	87	87	28	18
10	West	111	104	31	26
	East	93	88	29	20
11	West	132	119	37	30

Mean of the whole twenty-three lengths:

Number of Miners	per length	96·2
„ Labourers		95·0
„ Horses		28·9
„ Shifts		22·1

Through a misunderstanding on the part of the person who noted the amount of labour expended on the works, the particulars of the first side lengths at Saltwood were not recorded; but those of six of the second side lengths were noted, and are given in the following table:—

NUMBER OF MEN AND HORSES

Employed in excavating six of the second Side Lengths at Saltwood.

Number of Shaft.	Number of Men and Horses employed in driving top Heading.			To top Sill.			To middle Sill.			To bottom Sill.			Invert.			TOTAL.		
	Miners.	Labourers.	Horses.	Miners.	Labourers.	Horses.	Miners.	Labourers.	Horses.	Miners.	Labourers.	Horses.	Miners.	Labourers.	Horses.	Miners.	Labourers.	Horses.
1	3	3	1	14	18	6	21	27	10	16	22	6	9	13	3	63	83	26
2	2	3	1	13	20	6	22	28	8	18	23	6	8	12	3	63	86	24
3	2	4	1	23	34	10	19	25	7	14	17	5	11	13	4	69	93	27
4	2	4	1	21	29	8	18	21	6	14	[illegible]	6	11	14	4	66	86	25
5	2	3	1	13	24	8	11	16	4	16	23	6	10	15	4	52	81	23
6	Not	wor	ked	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
7	3	3	1	15	27	8	11	16	4	16	24	6	12	18	6	57	88	25

Mean of the whole six lengths :

Number of Miners	per length	61·6
„ Labourers		86·1
„ Horses		25·0

As the above statistical observations upon the side lengths at Saltwood were made in so much detail through each stage of the work, it may be useful to draw therefrom the following *average* amount of labour expended upon each portion or subdivision of the work.

AVERAGE AMOUNT OF LABOUR

Expended in each portion of the Excavation and Timbering the six Side Lengths at Saltwood Tunnel.

	Getting in the Tops.		Middle Sill.	Bottom Sill.	Invert.	Total.
	Top Heading.	Top Sill.				
Miners	2·33	16·50	17·00	15·66	10·16	61·65
Labourers	3·33	25·33	22·16	21·16	14·16	86·14
Horses	1·00	7·66	6·50	5·83	4·00	24·99

The amount of labour, and hence the cost of getting in the tops—which is always the most costly part of the miners' work, in tunnelling operations—may be found from the sum of the first two columns of the above table.

By comparing the results of the preceding tables, pages 159 and 160, it appears that less labour was required for the excavation of the side lengths at Saltwood than at Blechingley. This arose from the unexpectedly more favourable character of the ground after it had been so effectually drained by the construction of the headings. The comparison is shown in the following table ; but more extended remarks upon this subject will be made in a subsequent chapter, when there will be an opportunity of making a fairer comparison by means of the results of the leading lengths.

	Blechingley.	Saltwood.	Difference.
Miners	96·2	61·6	34·6
Labourers	95·0	86·1	8·9
Horses	28·9	25·0	3·9
Shifts	22·1		

Upon examining the preceding table for Blechingley, it will be observed that the west side length of each pit (which was the first that was excavated) occupied more time and labour than the east or second excavated length. This may appear remarkable, as it would naturally be expected that the two corresponding lengths in each pit would give a similar result, inasmuch as they were excavated by the same men, and under similar circumstances. It may, however, be accounted for by supposing that, at the first opening of new ground which was understood to be heavy, a greater degree of caution was used by the workmen, and, consequently, their proceedings were slower than when, by completing one length, they had become familiar with the peculiarities of the soil.

When it is stated that the work required 96·2 miners, 95 labourers, &c. it is meant that the labour was equal to 92·6 miners working one day (or shift), or one miner working 92·6 days.

The cost to the contractors for excavating the side lengths at Blechingley would, upon an average, be as follows:—

			£	s.	d.
Miners	. 96·2 days	. at 6*s*.	28	17	2
Labourers	. 95·0 „	. at 3*s*. 6*d*.	16	12	6
Horses	. 28·9 „	. at 7*s*.	10	2	4
Candles	. 4 dozen	. at 6*s*. 6*d*.	1	6	0
Gunpowder	. 1¼ cwt.	. at 46*s*.	2	17	6
Tools, and sharpening picks, wedges, &c.			1	5	0
Contractors' superintendence, 22 days at 7*s*.			7	14	0
Clearing up the work when completed, per length			0	5	0
Total			£68	19	6

Thus the cost to the contractor averaged 68*l*. 19*s*. 6*d*. per length of 12 feet.

In making the engagement with the gangers or sub-contractors, a price per lineal yard, for the side and shaft lengths taken together, was agreed upon, which price was 15*l*., or 60*l*. for each side length, they to find all manual and horse labour, candles, gunpowder, working tools, &c. Now it was well known that at such a price no profit could be derived from the side lengths, as the working expenses would, upon an average, exceed such price, which was

proved by the result, as shown above; but, taken together with the shaft lengths, which, at the same time that they were longer than the side lengths, required *much less time and labour to construct*, they yielded a fair amount of profit. When the particulars of the shaft lengths have been given, this subject will be recurred to, for comparison between the actual average cost and the price paid to the contractors.

When the *leading* lengths were in progress, the miners obtained a bonus, in a charge to the bricklayers of 3*l.* per length for lowering their materials, as bricks, cement, &c. to the underground works; which was done by loading the descending skip at the time that the earth from the excavation was being raised in the other. This yielded a profit of about 2*l.*, the third pound being paid for extra labour in loading the bricks, &c. and the loss of time occasioned to the miners' own work. But during the construction of the *side* and *shaft* lengths no such profit could be obtained, because the excavation was at a total stand, whilst the bricklayers were at work in each of these three lengths: whereas, during the progress of the *leading* work, the bricklayers would be proceeding at one end, from the shaft, whilst the miners would be progressing at the other, and *vice versâ*, whereby the earth excavated by the latter could be raised to the surface at the same time and by the same power that the materials of the former were lowered.

The observations made of the side lengths at Saltwood, as given at page 92, comprising as they do but one set of side lengths only, are, perhaps, not sufficiently extensive to warrant an investigation of their average cost to the sub-contractor, as done above in the case of Blechingley; but, if it be found desirable, such cost may be deduced by the aid of the above investigation of the side lengths at Blechingley and of that which will be given in a subsequent chapter upon the leading lengths at Saltwood. The item for the gunpowder must be omitted from such an investigation, as none of that material was used in the last-mentioned work. The quantity of candles consumed and the charge for superintendence must also be taken in proportion to the comparative quantity of time consumed in executing the work.

COST AND PROGRESS OF THE BRICKWORK OF THE SIDE LENGTHS.

The bricks were all made on the ground, and wheeled or carted to the various shafts. Their cost when thus delivered at the pit's mouth, including waste and all other expenses incurred, was 2*l.* 1*s.* 6*d.* per thousand. A portion of the bricks was made during the winter of 1840, and dried in flues by coal fires, which increased the cost considerably. [See paper by the Author, on this subject, read before the Institution of Civil Engineers, April 25, 1843.]

The price paid for brickwork at Blechingley was 4*l.* 10*s.* per rod, which included the setting and moving forward the centres—all tools, candles, and lowering of the materials from the surface to the underground works, procuring water where required, &c.

TABLE SHOWING THE PROGRESS OF THE BRICKWORK

In the construction of the Side Lengths at Blechingley Tunnel.

Number of Shaft.		Ground Mould Set.	Side Walls Springing high.	Arch Keyed in.
1*a*	West	March 25	March 27	March 31
	East	April 14	April 17	April 22
1	West	March 13	March 16	March 19
	East	April 2	April 5	April 8
2	West	April 9	April 4	April 7
	East	April 19	April 21	April 24
3	West	March 1	March 4	March 7
	East	March 22	March 24	March 26
4	West	March 12	March 14	March 17
	East	March 31	April 3	April 5
5	West	April 29	May 1	May 4
	East	May 14	May 15	May 18
6	West	April 14	April 16	April 18
	East	April 29	May 1	May 4
7	West	May 6	May 8	May 11
	East	May 22	May 24	May 26
8	West	May 12	May 14	May 17
	East	May 25	May 27	May 29
9	West	April 14	April 16	April 18
	East	April 30	May 1	May 4
10	West	April 7	April 9	April 12
	East	April 24	April 26	April 28
11	West	March 22	March 24	March 27

From the preceding table the following mean results are obtained:—

Shaft.	Time occupied in the construction of the Invert and Side Walls.	Time occupied in setting the Centres and turning the Arch.	Total Time occupied in constructing a Length.
	Days.	Days.	Days.
1*a*	2·5	4·5	7·0
1	3·0	3·0	6·0
2	2·0	3·0	5·0
3	2·5	2·5	5·0
4	2·5	2·5	5·0
5	1·5	3·0	4·5
6	2·0	2·5	4·5
7	2·0	2·5	4·5
8	2·0	2·5	4·5
9	1·5	2·5	4·0
10	2·0	2·5	4·5
11	2·0	3·0	5·0

Mean result of the whole table :—

	Days.
Time occupied in the construction of the Invert and Side Walls .	2·13
Time occupied in setting the Centres and turning the Arch .	2·83
Total time occupied in constructing a Side Length .	4·96

The number of men and horses employed in the above work was not registered.

For reasons stated at page 162, the particulars of the brickwork of the first side lengths at Saltwood were not recorded; but the following table gives all the requisite information respecting the second side lengths

TABLE SHOWING THE TIME AND FORCE

Employed in the Construction of Ten Side Lengths at Saltwood Tunnel.

West Side Lengths.		Number of Men and Horses on the Invert.				Number of Men and Horses on the Side Walls.				Number of Men and Horses on the Arch.			Total number of Men and Horses completing the Length.		
Number of the Shaft.	Ground Moulds set.	Bricklayers.	Labourers.	Horses.	Springing high.	Bricklayers.	Labourers.	Horses.	Keyed in.	Bricklayers.	Labourers.	Horses.	Bricklayers.	Labourers.	Horses.
1	Nov. 23	10	25	4½	Nov. 26	10	25	4½	Dec. 1	18	36	0	38	86	18
2	23	10	25	4½	26	12½	26½	6¼	1	18	40	9	40½	91½	19¾
3	25	8	22	4	29	10	20	4½	2	18	42	9	36	84	17½
5	26	8	22	4	29	10	22	4½	2	18	42	9	36	86	17½
4	23	10	24	4½	25	10	20	4½	Nov. 30	14	32	7	34	76	16
6	Not worked	—	—	—	—	—	—	—	—	—	—	—	—	—	—
7	23	11	23	4¾	26	11	23	4¾	30	18	42	9	40	88	18½
8	24	14	28	6	28	9	21	4¼	Dec. 2	14	32	7	37	81	17¼
9	21	8	20	4	23	8	20	4	Nov. 26	14	32	7	30	72	15
10	Not worked.	—	—	—	—	—	—	—	—	—	—	—	—	—	—
11	24	8	20	4	28	8	20	4	Dec. 3	14	33	7	30	73	15
12	25	12	26	6	29	10	22	4½	3	18	42	9	40	90	19½

From the preceding table the following mean results are obtained :—

	Days.
Time occupied in the construction of the Invert and Side Walls . .	. 3·2
Time occupied in setting the Centres and turning the Arch . . .	. 4·1
Total time occupied in constructing a Side Length . . .	. 7·3

MEAN OF THE FORCE EMPLOYED.

	In constructing			
	Invert.	Side Walls.	Arch.	Total in Length.
Bricklayers . .	9·90	9·85	16·40	36·15
Labourers . .	23·50	21·95	37·30	82·75
Horses . . .	4·63	4·60	8·20	17·43

By comparing the results of the above table and that at page 166, it will be seen that more time was taken by the bricklayers in the construction of the side lengths at Saltwood than was employed, for the similar work, at Blechingley: the former occupying 7·3 days, and the latter but 4·96 days.

LABOUR AND COST OF THE EXCAVATION OF THE SHAFT LENGTHS.

The time and force employed in the excavation of the shaft length, page 114, are given in the following statements :—

NUMBER OF MEN AND HORSES, AND THE NUMBER OF SHIFTS,

Employed in the Excavation of the Shaft Lengths at Blechingley.

Number of Shaft.	Miners.	Labourers.	Horses.	Shifts.
1*a*	56	58	15	14
1	52	41	14	12
2	42	45	14	11
3	55	57	15	12
4	48	46	16	11
5	38	42	16	11
6	37	39	14	10
7	38	43	13	10
8	40	40	15	11
9	43	40	15	10
10	55	53	18	12
11	Not	noted.	—	—

Mean of the whole eleven Lengths:

Number of Miners	45·8
„ Labourers	45·8
„ Horses	15·0
„ Shifts	11·3

From the preceding results, the average cost to the ganger or sub-contractor may be deduced in the same manner as done for the side lengths at page 164 ; thus :—

				£	s.	d.
Miners	45·8 days, at	6*s*.	. . . .	13	14	9
Labourers	45·8 „	3*s*. 6*d*.	. . . .	8	0	4
Horses	15·0 „	7*s*.	. . . .	5	5	0
Candles	2 dozen	6*s*. 6*d*.	. . . .	0	13	0
Gunpowder	1 cwt.	46*s*.	. . . .	2	6	0
Tools, and sharpening picks, wedges, &c.			. . . . . .	1	5	0
Contractors' superintendence, 11·3 days, at 7*s*.			. . . . .	3	19	1
Clearing up the work when completed, per length			. . . .	0	5	0
		Total	. . . .	£35	8	2

At page 164 it has been shown that the excavation of the side lengths alone, at 15*l.* per lineal yard, would have been a losing concern; but it was there stated that, taken together with the shaft lengths, a fair profit was obtained; this may now be shown, as follows:—

COST OF EXCAVATION.

		£	s.	d.
Two side lengths, each 68*l.* 19*s.* 6*d.* . . .	=	137	19	0
Shaft length, as above	=	35	8	2
Total cost to the ganger .	=	£173	7	2

The side lengths were each 12 feet in length, and the shaft lengths averaged 14 feet, making 38 feet for the three lengths; which, at 15*l.* per yard, or 5*l.* per foot, gave 190*l.* to be received by the ganger for the work, which cost, upon an average, 173*l.* 7*s.* 2*d.*; leaving a clear profit of 16*l.* 12*s.* 10*d.*, or at the rate of about 8½ per cent.

The following table will show the amount of labour, &c., consumed in the excavation of six shaft lengths at Saltwood:—

NUMBER OF MEN AND HORSES

Employed in the Excavation of six of the Shaft Lengths at Saltwood.

Number of Shaft.	Miners.	Labourers.	Horses.
1	49	57	20
2	51	58	20
3	51	60	21
4	52	59	20
5	48	56	19
6	Not worked.		—
7	52	59	18

Mean of the whole six Lengths:

Number of Miners	50·5
„ Labourers	58·2
„ Horses	19·7

By comparing the above table with that at page 169, it will be seen that more labour was expended upon the shaft lengths at Saltwood than was

required for the similar work at Blechingley; and that such a result is the reverse of that obtained by comparing the labour of the side lengths, as at page 163, and is also contrary to the result of a comparison of the leading work, as will afterwards be shown. The greater amount of labour required for the shaft lengths at Saltwood must have arisen from the circumstance that great caution and expenditure of time was there required in removing the timbers about the shaft, in timbering the length, and in making all solid where the running of the sand, during the shaft sinking, had left large vacuities.

LABOUR AT CURBS OF SHAFTS OF BLECHINGLEY TUNNEL.

The annexed table shows the amount of labour required in constructing the curb, page 118, at each shaft of Blechingley Tunnel :—

NUMBER OF MEN AND HORSES

Employed in constructing the Brick Curbs to the Shafts at Blechingley Tunnel.

Number of Shaft.	Bricklayers.	Labourers.	Horses.
1*a*	67·7	59·0	20·0
1	72·7	93·5	18·3
2	59·5	72·5	17·0
3	60·0	74·3	22·5
4	64·7	78·3	21·3
5	66·7	65·0	18·0
6	73·7	93·0	21·3
7	77·7	82·0	22·0
8	68·7	101·0	16·0
9	64·7	65·7	17·3
10	60·0	69·3	17·3

Mean of the whole Eleven Shafts :

Bricklayers . . . . . . 66·9
Labourers . . . . . . 77·6
Horses . . . . 19·2

LABOUR AND COST OF THE EXCAVATION OF THE LEADING LENGTHS.

The amount of labour consumed and the cost of the work, page 120, are given in the following statements :—

NUMBER OF MEN AND HORSES, AND THE NUMBER OF SHIFTS

Employed in the Excavation of the Leading Lengths at Blechingley Tunnel.

Number of Shaft.	Number of Lengths constructed from each Shaft.	Average Number in each Shaft of			
		Miners.	Labourers.	Horses.	Shifts.
1*a*	21	52·1	71·7	15·1	14·3
1	23	42·8	53·9	12·5	11·8
2	24	47·3	65·8	14·7	9·0
3	24	53·1	67·8	16·8	9·5
4	22	51·7	78·4	18·4	10·1
5	16	51·3	79·1	17·4	9·6
6	19	52·4	72·4	18·2	11·0
7	19	48·5	63·5	14·8	8·8
8	20	39·5	54·3	12·4	6·9
9	20	51·6	70·4	16·5	9·4
10	21	64·5	74·8	18·5	10·5
11	11	88·8	112·7	30·8	25·4

Mean of the whole two hundred and forty lengths:

Number of Miners, per length	52·2
,, Labourers ,, ...	70·1
,, Horses ,, ...	16·5
,, Shifts ,, ...	10·8

The number of workmen employed in a length will vary in different parts of the work as it advances. In driving the top heading, one or two miners and one labourer only can be employed; then, in getting in the tops and before they have commenced drawing the earth, the numbers will be about three or four miners and three labourers; and when the earth is being drawn to the surface the greatest force can be put on, which amounts to about five miners, three labourers attending upon them, one hooker-on, and four banksmen.

Upon inspecting the preceding table it will be seen that No. 11 shaft employed the greatest force, and took the most time; this arose from the ground being so very heavy where it was shallow, near the entrance of the tunnel, as described in the general particulars of the tunnel, at pages 15 and 16.

It may also be observed that the amount of labour for the leading work

portion of the work yielded a deal of water, and was extremely heavy, which brought up the average as above stated.

By means of the table at page 172 the average cost to the contractor may be ascertained, and compared with the contract price and the estimate given above.

AVERAGE COST OF EXCAVATING

The Leading Lengths at Blechingley.

				£	s.	d.
Miners	52·2 days, at	6s.	. . . .	15	13	2
Labourers	70·1 „	3s. 6d.	. . .	12	5	4
Horses and drivers	16·5 „	7s.	. . .	5	15	6
Candles	3 dozen	6s. 6d.	. . .	0	19	6
Gunpowder	1 cwt.		. . . . .	2	6	0
Tools, and sharpening picks, wedges, &c.			. .	1	5	0
Contractors' superintendence, 10·8 days, at 7s.			.	3	15	7
Clearing up the work when completed, per length				0	5	0
		Total	. . . . .	£42	5	1

Which, divided by 4, gives 10*l.* 11*s.* 3*d.* per lineal yard.

Thus the cost to the contractor averaged 42*l.* 5*s.* 1*d.* per length, and the amount he received averaged 44*l.*—leaving a profit of 1*l.* 14*s.* 11*d.* To this may be added 3*l.*, which the bricklayers paid to the miner, per length, for lowering bricks, cement, and sand, down the shaft, at the same time that they were raising the earth to the surface; this, however, would require one or two additional labourers to load the bricks, &c. into the skips, and would take 1*l.* away from the 3*l.*, leaving 2*l.* to be added to the above 1*l.* 14*s.* 11*d.*, making together 3*l.* 14*s.* 11*d.* as the profit per length—being at the rate of about 8½ per cent.

The above is about the average result of the works at Blechingley. In some cases the work did not cost so much money to execute it, and in some it cost more. There were several cases in which the contract price would not cover the outlay, and the gangers at such shafts gave up the work. Upon the whole, the above statement appears to be a fair representation of the cost for executing the work at Blechingley.

The following statement comprises a similar investigation of the works at Saltwood :—

AVERAGE NUMBER OF MEN AND HORSES, AND THE NUMBER OF SHIFTS

Employed in the Excavation of the Leading Lengths at Saltwood Tunnel.

Number of Shaft.	Number of Lengths constructed from each Shaft.	Miners	Labourers.	Horses.	Number of Shifts. Before drawing earth.	While drawing earth.	Total.
1	17	45·3	50·3	12·8	3·3	7·2	10·5
2	18	42·1	50·1	15·3	2·5	7·2	9·7
3	20	39·2	54·3	15·3	2·7	7·1	9·8
4	18	36·5	54·7	14·4	3·2	6·6	9·8
5	22	33·3	50·6	13·2	2·7	6·1	8·8
6	Not worked.		—	—	—	—	—
7	20	34·3	53·6	14·0	2·5	6·5	9·0
8	19	34·6	50·6	13·4	2·7	6·2	8·9
9	20	34·6	53·3	13·8	2·9	6·2	9·1
10	17	34·3	55·2	14·3	2·8	6·3	9·1
11	15	35·3	57·1	14·8	3·1	6·6	9·7
12	6	34·7	56·3	14·5	3·1	6·4	9·5

Mean of the whole one hundred and ninety-two lengths:

Number of Miners, per length	36·8
„ Labourers „	53·0
„ Horses „	14·1
„ Shifts „	9·4

The preceding table shows the average amount of labour and time expended in the construction of the leading lengths at Saltwood Tunnel. The cost thereof would be approximately as follows :—

AVERAGE COST OF EXCAVATING

The Leading Lengths at Saltwood.

			£	s.	d.
Miners .	36·8 days, at	5s.	9	4	0
Labourers .	53 „	3s. 3d. . .	8	12	3
Horses and drivers	14·1 „	7s.	4	18	8
Candles .	2½ dozen	6s. 6d. . .	0	16	3
Tools, and sharpening picks, wedges, &c. . .			1	0	0
Contractors' superintendence, 9 days, at 7s. .			3	3	0
Clearing up the work when completed, per length			0	5	0
Total			£27	19	2

Which, divided by 4, gives 6*l.* 19*s.* 9*d.* per lineal yard.

The prices of the miners' and labourers' wages are put above at 5*s.* and 3*s.* 3*d.* per diem ; whereas, for the same class of men, in the investigation of the cost of Blechingley they were reckoned at 6*s.* and 3*s.* 6*d.* The fact was as stated in each case, for the wages were higher at the time Blechingley Tunnel was in hand than they were two years later, when Saltwood Tunnel was constructed; because so many similar works were proceeding at the time that the former tunnel was made, which led to a demand for men who were accustomed to the work ; whereas two years later no such demand for workmen existed.

At Saltwood, the contractors supplied the horse power themselves, and let the manual labour only to the sub-contractors.

LABOUR AND TIME IN EXCAVATING AND TIMBERING SALTWOOD TUNNEL FROM THE OPEN END.

The following table shows the average amount of labour and time expended in excavating and timbering each 12-feet length, from the open end, as above described :—

Number of Lengths	7
" Miners	34·3
" Labourers	40
" Horses	11
" Shifts	9·7

By placing the mean results of the tables in pages 172 and 175 in juxtaposition, it will be seen how much more labour was required in the excavation of the leading work at Blechingley than was necessary at Saltwood. This could not arise from any difference in the skill of the workmen, as a large portion of the same men were employed in both cases; and all the gangers or sub-contractors at Blechingley were the most experienced men that could be found: the difference arose from the varied character of the ground in the two cases. At Blechingley it was a strong blue clay, highly indurated into a hard shale or bind requiring the aid of gunpowder to get it,

and when exposed to moisture or the air it swelled and afterwards slaked; there was also some water to contend with. At Saltwood, after the preliminary works were completed, which had drained off the water most effectually, the ground was a dry sand, except at the level of the invert, where but little trouble was experienced from the water, as the heading afforded so excellent a means of letting it off. Admitting, therefore, that equal skill was employed in both cases, the following table will show the amount of labour required for excavating the leading work, in the two kinds of earth, and may serve as a useful guide in future operations:—

	Blue Shale.	Dry Sand.	Difference in favour of Sand.	Approximate Ratio of the Sand to the Shale.
Miners	52·2	36·8	15·4	0·7 } mean, 0·8
Labourers	70·1	53·0	17·1	0·7
Horses	16·5	14·1	2·4	0·8
Shifts	10·8	9·4	1·4	0·9

Or, the amount of labour and time required to excavate for tunnelling through dry sand may be said to be approximately eight-tenths of that required to do the same work in blue clay or bind.

BRICKLAYERS' WORK FOR THE LEADING LENGTHS.

The following table shows the work done at Blechingley. The reason that there is so little variation in the amount of labour and time required for the brickwork arises from the fact that the circumstances are nearly always alike, this kind of work not being subject to such vicissitudes as that of the miners.

AVERAGE TIME TAKEN BY THE BRICKLAYERS

To turn twelve feet Leading Lengths at Blechingley Tunnel.

Number of Shaft.	Number of Lengths.	From setting the Ground Mould to the springing of the Arch.	From the springing of the Arch to Keying-in.	Total.	Force Employed.	
					Bricklayers.	Labourers.
		Days.	Days.	Days.		
1a	17	2·3	2·6	4·9	4	7
1	20	2·2	2·9	5·1	4	7
2	23	1·9	2·4	4·3	4	7
3	23	1·8	2·2	4·0	4	7
4	21	1·9	2·4	4·3	4	7
5	15	1·7	2·5	4·2	4	7
6	18	1·8	2·2	4·0	4	7
7	17	1·7	2·5	4·2	4	7
8	19	1·6	2·1	3·7	4	7
9	20	2·0	2·5	4·5	4	7
10	20	1·7	2·1	3·8	4	7
11	12	2·0	3·0	5·0	4	7

The result of the preceding table :

	Days.
Time occupied in the construction of the invert and side walls . .	1·88
Time occupied in setting the centres and turning the arch . .	2·42
Total time occupied in constructing a leading length . .	4·30

LABOUR AND COST OF CULVERTS.

The following table shows the amount of labour and the cost of constructing the culvert through Blechingley Tunnel (page 138)—1,324 yards lineal—with the radiating bricks and the above-described centre :—

	Horses.	Bricklayers.	Labourers.
	Days.	Days.	Days.
Carting bricks . . .	71	—	—
Lowering bricks and mortar	43½	—	68¼
Turning culvert . .	—	151¾	167½
Loading brick carts, &c. .	—	—	35
Wheeling bricks at top .	—	—	252½
„ in tunnel .	—	—	44
Making mortar . . .	—	—	30¾
Banking	—	—	16
Total . . .	114½	151¾	614¼

ACTUAL COST.

				£	s.	d.
120,000 bricks, including waste,		at 50*s*. per thousand . .	=	300	0	3
Materials consumed.	75 bushels of cement	at 1*s*. 8*d*. per bushel . .	=	6	5	0
	48 yards of lime	at 13*s*. per yard . .	=	31	4	0
	96 yards of sand	at 1*s*. " . .	=	4	16	0
	Carting ditto	at 2*s*. " . .	=	9	12	0
	Carting water		.	2	5	6
	Candles, 410 lbs.	at 6½*d*.	=	11	2	1
Labour	Horses 114½ days,	at 7*s*.	=	40	1	6
	Bricklayers 151¾ "	6*s*.	=	45	10	6
	Labourers 614¼ "	3*s*. 3*d*.	=	99	16	4
				550	12	11
	Centre, as above described		.	10	0	0
		Total	.	£560	12	11

Being at the rate of 8*s*. 5½*d*. per yard forward.

The weight of ironwork to the centres, including axles to the rollers, was 181 pounds.

Had the culvert at Blechingley been built in two rings, with common bricks, it would have taken 264 to a yard forward, or 350,000 in the whole.

COST OF CENTRES.

The cost of setting the centres (page 144) and removing them forward was included in the price of the brickwork, namely, 4*l*. 10*s*. per rod. This work was performed by a gang of men who devoted their whole time to it, and contracted with the several bricklayers to do this part of their work; and thus by constant practice they obtained a readiness in its execution.

The price paid by the bricklayers at first was 3*l*. per set, but this was subsequently reduced to 2*l*. 10*s*.—the centre setters finding all necessary tools, candles, &c.

The following will show the total cost of a double set of centres, and the

requisite materials for one end of a shaft, the work proceeding as at Blechingley Tunnel:—

		£	s.	d.
2 leading or segment centres, at	£10 12s. 11d. each	21	5	10
3 scarf ditto	£9 4s. 6d.	27	13	6
2 sets of laggins	£6 10s. 0d.	13	0	0
2 sets of keying ditto	£1 0s. 0d.	2	0	0
3 centre sills and ironwork complete		13	5	6
8 half-timbers		4	7	11
14 props		3	19	4
6 collars		0	6	0
40 slack blocks		2	0	0
Total cost of materials		£87	18	1

The preceding prices were paid at Blechingley in 1841; but subsequently the duty on foreign timber has been greatly reduced, and therefore the same materials at the present time would not cost so much by a considerable amount.

The following table shows the total cost of a complete set of Frazer's patent centres (page 148), and the necessary materials for one end of a shaft, as used at Saltwood Tunnel:—

		£	s.	d.
Leading rib		9	3	3
Middle rib		6	6	8
Back rib		9	11	3
Jack rib		7	16	8
Irons for ribs		0	4	0
Two props for leading ribs,	£1 3s. 2d. each	2	6	4
Two trestles	£8 18s. 10d. „	17	17	8
One set of laggins—same as at Blechingley		6	10	0
One set of keying-in ditto	ditto	1	0	0
Total cost of materials		£60	15	10

Comparison.—A double set of Blechingley centres, with all the necessary materials to be used, as already described, cost, as above stated, the sum of 87*l.* 18*s.* 1*d.* If a single set be employed, as they might be with safety w· [illegible] ·hich is the plan frequently followed

by contractors), the cost would be 50*l.* 6*s.* 11*d.*, which exceeds half of the above sum, because more than one-half of that quantity of materials would be required.

The cost of a corresponding set of the patent centres would be, as shown above, 60*l.* 15*s.* 10*d.* (the prices of the materials being taken alike in both estimates for the sake of correct comparison). The patent centres would therefore be less costly than a double set of ordinary centres by 27*l.* 2*s.* 3*d.* and more costly than a single set by 10*l.* 8*s.* 11*d.*

It may also be considered that, when the work is completed, and the centres laid aside, the sills, half-timbers, and props, used with the ordinary centres, would be worth more money, as timber, than the pieces forming the trestles, &c. of the patent centres, because they would be less cut up into small pieces. The former, indeed, would be nearly as valuable as when first put into use for those purposes, if proper care had been taken of them. The real deduction from their original value would be the usual charge for use and waste.

HORSE POWER EMPLOYED IN WORKING THE GINS.

The expense of 67 horses, with attendants, per day of 24 hours, during the shaft-sinking and water-drawing at Saltwood Tunnel, in 1842 (page 79), was as follows:—

	£	s.	d.
Two quarters one bushel of beans, at 38*s.* per quarter .	4	0	9
,, ,, ,, oats 25*s.* ,, .	2	13	1
Fifty trusses of hay, £5 10*s.* per ton of 40 trusses	6	17	6
Forty ,, straw 8*d.* per truss .	1	6	8
Shoeing each horse . . per diem 1*d.*	0	5	7
Farriers' expenses, per horse ,, 3*d.*	0	16	9
Stabling . . ,, ,, 3*d.*	0	16	9
Harness and repairs ,, ,, 3*d.*	0	16	9
Twelve stablemen . . . . ,, 3*s.* each . . .	1	16	0
Eighteen gin-boys . . . . ,, 1*s.* 3*d.* ,, . . .	1	2	6
Eighteen ,, . . per night, 1*s.* 6*d.* ,, . . .	1	7	0
	£21	19	4

Being at the rate of 6*s.* $6\frac{7}{10}$*d.* per diem for each horse.

They were supplied with as much food as they could eat, not only in the stable but at every interval of rest during the time of working.

The average time made by each horse was 1·11 shifts per diem, which, at 7*s.* per shift, gave 7*s.* $9\frac{2}{10}$*d.* as the earnings of each horse; leaving 1*s.* $2\frac{1}{2}$*d.* per diem to cover contingencies arising from the death or depreciation in the value of the cattle.

The above table will give a good approximation to the quantity of food consumed by horses when working hard, and of the general expenses attending that kind of work. The cost of the corn and hay will of course vary from time to time. When the works were executed in which the horses above referred to were employed, the price of grain, &c. was very high.

ABSTRACT COST OF THE TUNNELS.

The total costs of the Blechingley and the Saltwood Tunnels are set forth in the following statements:—

ABSTRACT OF THE COST OF BLECHINGLEY TUNNEL.

	£ s. d.	£ s. d.	£ s. d.
MATERIALS:—			
Bricks	30,499 12 10		
Cement	11,016 0 11		
Timber	11,341 19 2		
Wrought and cast ironwork and ironmongery	2,499 3 1		
Miscellaneous: including pumps, weighing machine, broken stone for roads, lime, ropes, stationery, and all materials not included under any of the above heads	6,555 2 8		
		. .	61,911 18 8
LABOUR:—			
Mining. Shafts, heading, and preliminary works	3,273 2 8		
Mining. Driving the tunnel—including the hire of gin-horses, and the open excavation, for lengthening the tunnel	15,727 7 0		
		19,000 9 8	

ABSTRACT OF THE COST OF BLECHINGLEY TUNNEL—(CONTINUED).

		£ s. d.	£ s. d.	£ s. d.
Forward			19,000 9 8	61,911 18 8
Brickwork.	Shafts, and preliminary works .	378 8 0		
	Constructing the tunnel, and lengthening the tunnel in open excavation	11,265 4 11		
			11,643 12 11	
MISCELLANEOUS :— Including the erection of the tunnel entrances, culvert through the tunnel, part ballasting the tunnel, construction of machinery, erection of buildings, carpentry, sawing, clerks' and inspectors' wages, &c.			6,980 16 6	
				37,624 19 1
				99,536 17 9
Deduct estimated value of plant, removed to Saltwood upon the completion of Blechingley Tunnel				4,300 0 0
Total cost of Blechingley Tunnel . . .				95,236 17 9

Being at the rate of 71*l.* 18*s.* 7*d.* per lineal yard for the whole tunnel; 1,324 yards in length, or three-quarters of a mile and four yards.

ABSTRACT OF THE COST OF SALTWOOD TUNNEL.

Expenditure previous to the time that the Works were contracted for.

	For Preliminary Works.	For the Tunnel.	Sums.
MATERIALS :—	£ s. d.	£ s. d.	£ s. d.
Bricks, including carting . .	3,210 17 3	14,527 12 7	17,738 9 10
Cement	—	253 2 6	253 2 6
Lime	50 14 4	—	50 14 4
Timber	1,928 9 4	1,420 1 4	3,348 10 8
Ironwork and ironmongery . .	317 5 5	159 2 2	476 7 7
Straw	119 7 10	—	119 7 10
Ropes	86 8 9	—	86 8 9
Cottages, office, store, &c. . .	62 0 0	248 0 0	310 0 0
Roads along the whole of the works	70 0 0	400 18 7	470 18 7
Miscellaneous materials . . .	519 2 3	187 17 2	706 19 5
Plant from Blechingley Tunnel .	1,433 0 0	2,867 0 0	4,300 0 0
	7,797 5 2	20,063 14 4	27,860 19 6

ABSTRACT OF THE COST OF SALTWOOD TUNNEL—(CONTINUED).

	For Preliminary Works.			For the Tunnel.			Sums.		
	£	s.	d.	£	s.	d.	£	s.	d.
Forward	7,797	5	2	20,063	14	4	27,860	19	6
CARTING AND HORSE-HIRE:—									
Carting on works	251	9	2	103	15	6	355	4	8
Hire of gin-horses	1,585	15	3	—			1,585	15	3
Materials from Blechingley Tunnel	315	11	9	631	3	5	946	15	2
Freight, &c.	120	0	0	292	18	0	412	18	0
LABOUR:—									
Mining	3,477	11	11	—			3,477	11	11
Brickwork	217	3	4	—			217	3	4
Sawing	67	0	8	—			67	0	8
Miscellaneous	706	8	11	682	17	1	1,389	6	0
MISCELLANEOUS EXPENSES	70	10	0	—			70	10	0
TOTALS	14,608	16	2	21,774	8	4	36,383	4	6

This amount, added to the expenditure under the contract, will give the total cost of the Tunnel, as follows:—

ABSTRACT OF THE COST OF SALTWOOD TUNNEL.

Expenditure under the Contract, after the Preliminary Works were completed.

	£	s.	d.	£	s.	d.	£	s.	d.
Amount of contract				—			85,000	0	0
Hoop-bond joints				32	10	8			
TUNNEL ENTRANCES:—									
Excavation	75	8	9						
Brickwork	1,553	0	0						
				1,628	8	9			
							1,660	19	5
Additional brickwork				321	15	0			
" timber				176	8	0			
" labour				358	8	0			
Hard white bricks, for arch				2,948	3	6			
Broken stone for ballast				99	11	6			
Drains, cesspools, &c., at ends of Tunnel				386	5	10			
							4,290	11	10
							90,951	11	3

ABSTRACT OF THE COST OF SALTWOOD TUNNEL—(CONTINUED).

	£ s. d.	£ s. d.
Forward		90,951 11 3
DEDUCTIONS :—		
Tunnel, 10¼ yards short of 964 (the contract length)	825 2 6	
Saving in shafts closed	36 0 0	
Saving upon white brick not carted . . .	223 15 7	
Bricks for which the Company had previously paid [see page 183]	14,527 12 7	
		15,612 11 8
		75,338 19 7
Allow for plant, as per contract		3,006 0 0
		72,332 19 7

Now, if to the above sum be added the amount expended previous to letting the contract, as before set forth, and the wages afterwards paid to inspectors, &c., together with 3,006*l.*—the assumed value of the plant—the whole cost of the tunnel will be shown.

	£ s. d.
Preliminary works, and previous expenses	36,383 4 6
Payments under contract	72,332 19 7
Inspection, rent of land, sorting bricks, &c. . . .	820 1 5
Assumed value of plant	3,006 0 0
Total cost of Saltwood Tunnel .	£112,542 5 6

Being at the rate of 118*l.* per lineal yard for the whole Tunnel; 953¾ yards in length, or half-a-mile and 73¾ yards; but upon a very careful admeasurement the Tunnel proved to be very little short of 954 yards.

The bricks for Saltwood Tunnel had been contracted for previously to the author's leaving Blechingley: they were made at Folkestone, averaging five miles distant from the works; and the cost, when delivered, was 51*s.* per thousand.

CHAPTER XV.

ON TUNNELS AND TUNNEL-ENTRANCES.

Being Descriptions of Plates XIII. to XVI.

BY W. DAVIS HASKOLL, C.E.

As many varieties in the form of Tunnels, since the first edition of this work was issued, have been adopted by different engineers upon the respective lines under their control, to suit the various strata through which they had to pass, it has been thought necessary to give several additional plates, to show some of the figures that have been chosen for the purpose. These, with their descriptions, form the additional Appendix; their peculiarities will be best understood in the accompanying representations. Plate XIII. shows a tunnel entrance on the Wilts, Somerset, and Weymouth Railway for a double line, constructed with brickwork in mortar, having an internal width of 28 feet, with curved retaining side-wing walls. Sections of these are given at several places to show their construction and relative heights, thickness, and batter, and also the projecting footings of the set-offs, as well as the stepping-up of the wing-walls at the tunnel entrance. The whole of the work is finished with a plain weathered stone coping at a height of 29 feet above the line of rails.

The tunnel, which passes through a rocky strata, has a rusticated stone facing projecting outwards from the entrance face, with a batter of 1 in 20; the soffit of the arch being 28 feet above the rails. The crown of the tunnel gradually diminishes inwards the length of 35 feet 9 inches, after which it takes the form represented by the cross section. The points from which the radius of the crown, sides, and invert are struck, are shown by dotted lines.

The invert, curved side-walls, and arch is 2½ bricks thick, constructed

with five 4½-inch rings in mortar, the crown being turned in Roman cement. The ballast on the invert is 2 feet 6 inches deep in the centre, and the horizontal dotted line at the starting of the side-walls is the level of the rails. The thickness of the brickwork at A, on the longitudinal section, is shown in the plan, taken on the same line. Plate XIV.—The elevation here given is of the front of a tunnel on the South Wales Railway, having semi-elliptical retaining wing-walls, the entrance being 28 feet in width, and the longitudinal section, taken on the line A of the plan, shows the tunnel entrance. The brickwork above the centre of the tunnel is 5 feet in thickness, gradually diminishing to 2 feet 3 inches at the termination of each wing-wall, where it intersects the adjoining slopes of the excavation. The cross-sections, B, C, D, E, and F, show the relative heights and thicknesses of the brickwork and batter of the wing-walls; the corresponding letters of reference on the plan give the various dimensions at the same places. The parapet wall over the tunnel and wing-walls is weather-coped with stone 2 feet 3 inches wide and 12 inches thick. The bold projection surrounding the arch at the entrance is composed of rough-faced stonework, the keystone of which is 6 feet 6 inches in depth, and projects 2 feet 9 inches from the face of the tunnel. The stones forming each side of the arch from the keystone gradually diminish to 5 feet 6 inches in width, resting on a stone base 10 feet 6 inches wide, bedded in brickwork.

The soffit of the arch at the entrance is 28 feet above the level of the rails, gradually reducing to a point inwards 35 feet 9 inches from the tunnel face. The cross-section of this tunnel is similar to that shown in Plate XIII., except the brickwork, which is constructed with six 4½ rings in mortar, and the crown turned in cement.

The elevation shown in Plate XV. represents the entrance of a tunnel constructed on the Manchester and Leeds Railway, and tunnelled through rock for a single line of rail. The width is 15 feet, and the soffit 17 feet above the level of the rails. The side curved walls are founded in the rock at a depth of 3 feet 6 inches below the rails. The rock being of a sound compact nature, enabled the engineer to form the floor of the tunnel thereon, and consequently allowed him to dispense with the usual invert.

The centre portion of the tunnel face projects 3 feet before the curved side retaining wing-walls. The footings of the wing-walls are stepped up the slopes of the excavation, which are dressed off at a rate of $\frac{3}{4}$ to 1. The face of the arch is finished with a head and stretcher chamfered stone block-in course, as shown in the elevation. The tunnel face is surmounted by two rows of block-in course, each course sailing over 6 inches and finished by a stone pediment 20 feet long and 4 feet deep in the centre, and 2 feet 6 inches at the end, with return walls of the same height, 18 inches thick.

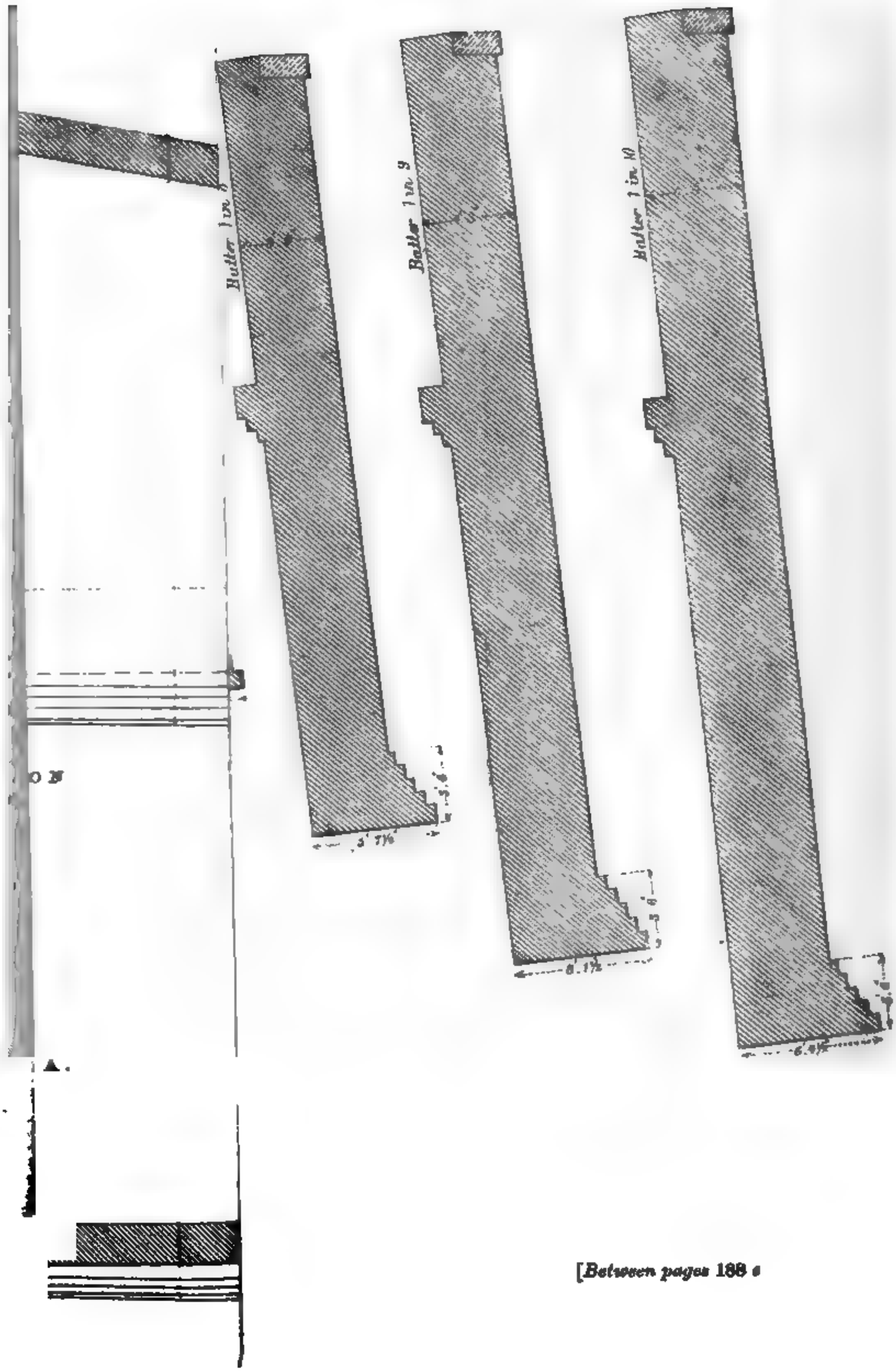
The slopes of the excavation are dressed down to $\frac{3}{4}$ to 1, and a puddle trench formed below the 6-inch stone pitching at the foot of the slope over the tunnel, to prevent any surface-water from gaining access to injure either the brickwork of the arch or the tunnel face. The pier-points at each end of the tunnel are constructed in Roman cement for about 20 feet.

The cross-section of the tunnel shows the position of the rails and the depth of ballast on the tunnel floor, which has a central drain, as shown in the section, covered with a selected 4-inch pavement, with open joints to allow any soaking to pass through into the drain. The thickness of the brickwork for the construction of the arch is fully given in the section.

The front elevation of the Birkenhead Tunnel (Plate XVI.), which is for a single line of railway, is built with chamfered ashlar facing, having a bold projecting stone cornice, surmounted with a parapet wall, finishing at each end with pilasters. The wing-walls are curved on the face, and run in the direction of the bottom of the slopes of the cutting, behind which are brick inverts laid along the slopes, to receive any surface-water and conduct it down to the open channels along the bottom of the slope of the excavation at each end of the tunnel entrances.

The width of the tunnel is 15 feet, and the soffit of the arch is 14 feet 6 inches above the line of rails. A stone channel runs on each side of the tunnel, at the bottom of the curved side walls, level with the top of the rails; these channels act as drains for the tunnel. The ballast is laid 1 foot 6 inches deep on the invert, and the sleepers are embedded in the ballast.

OUGH RETAINING WALLS.



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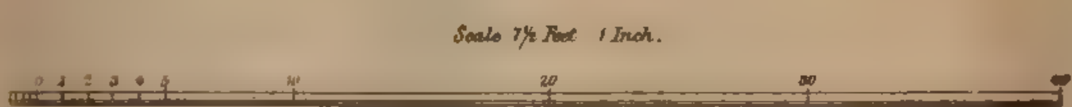
CROSS SECTION OF TUNNEL.



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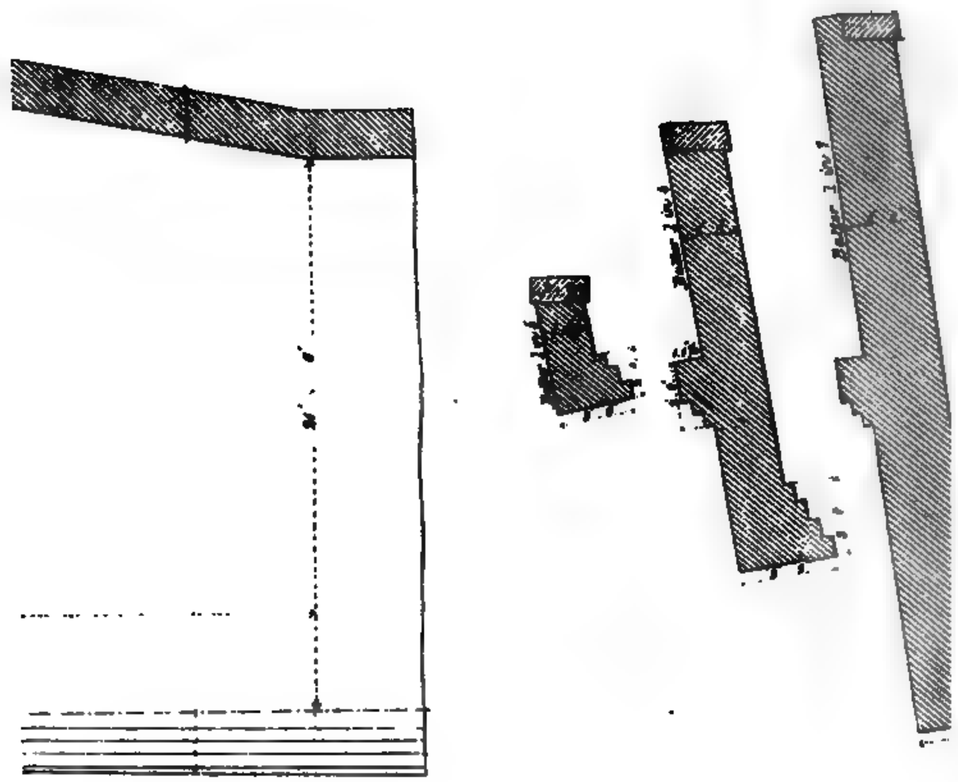
MERSET AND WEYMOUTH RAILWAY.

SECTIONS T



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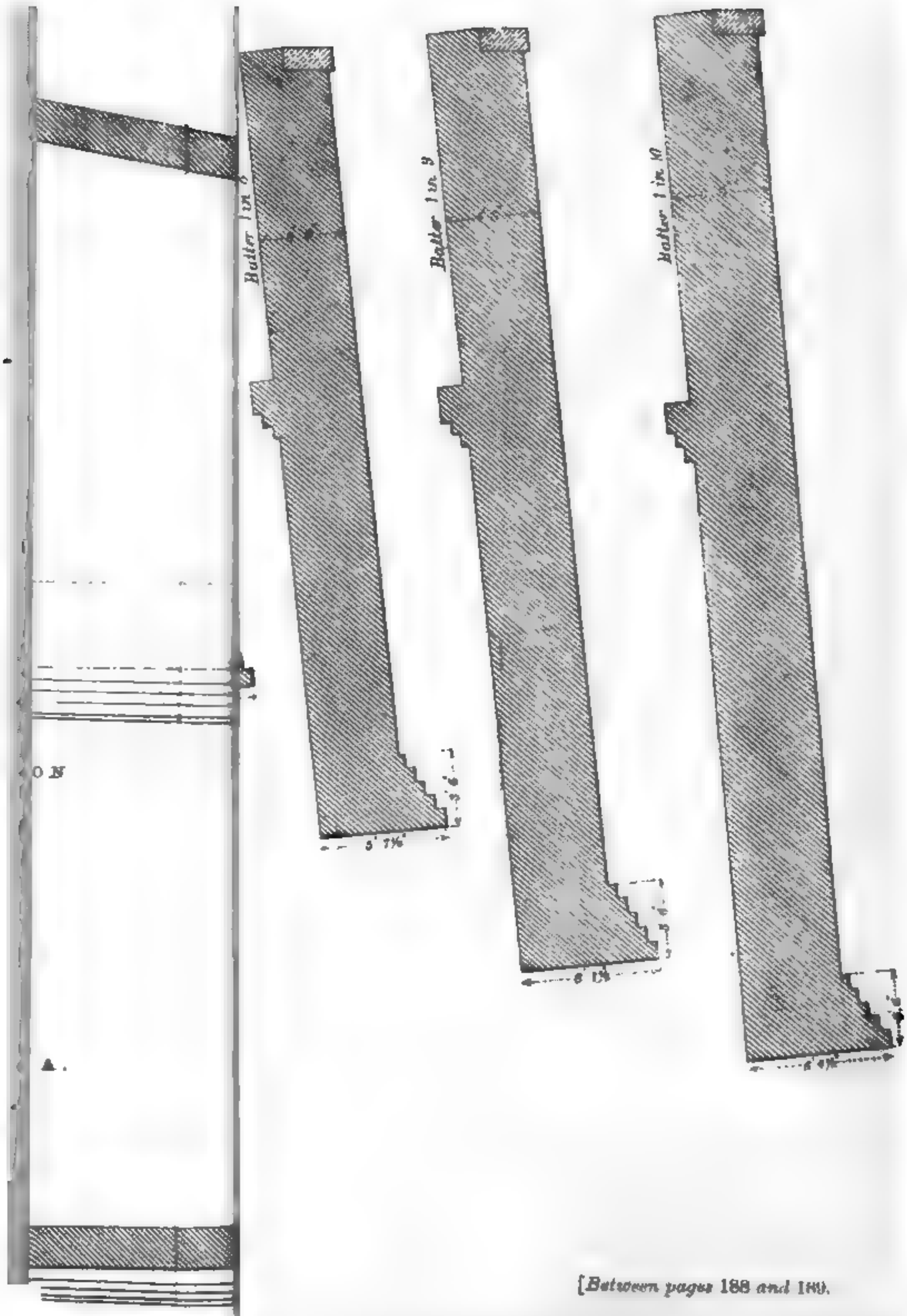

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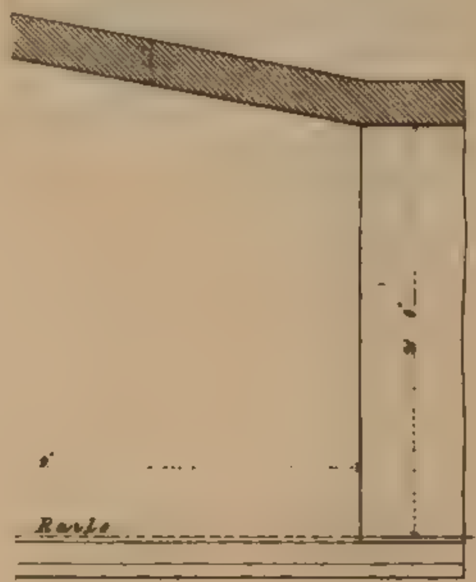

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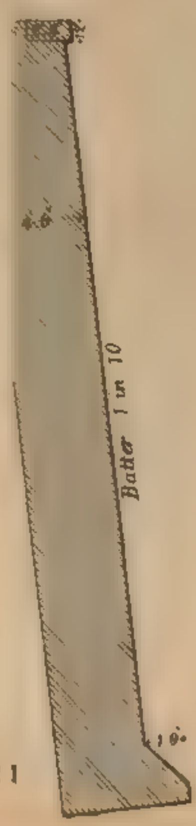

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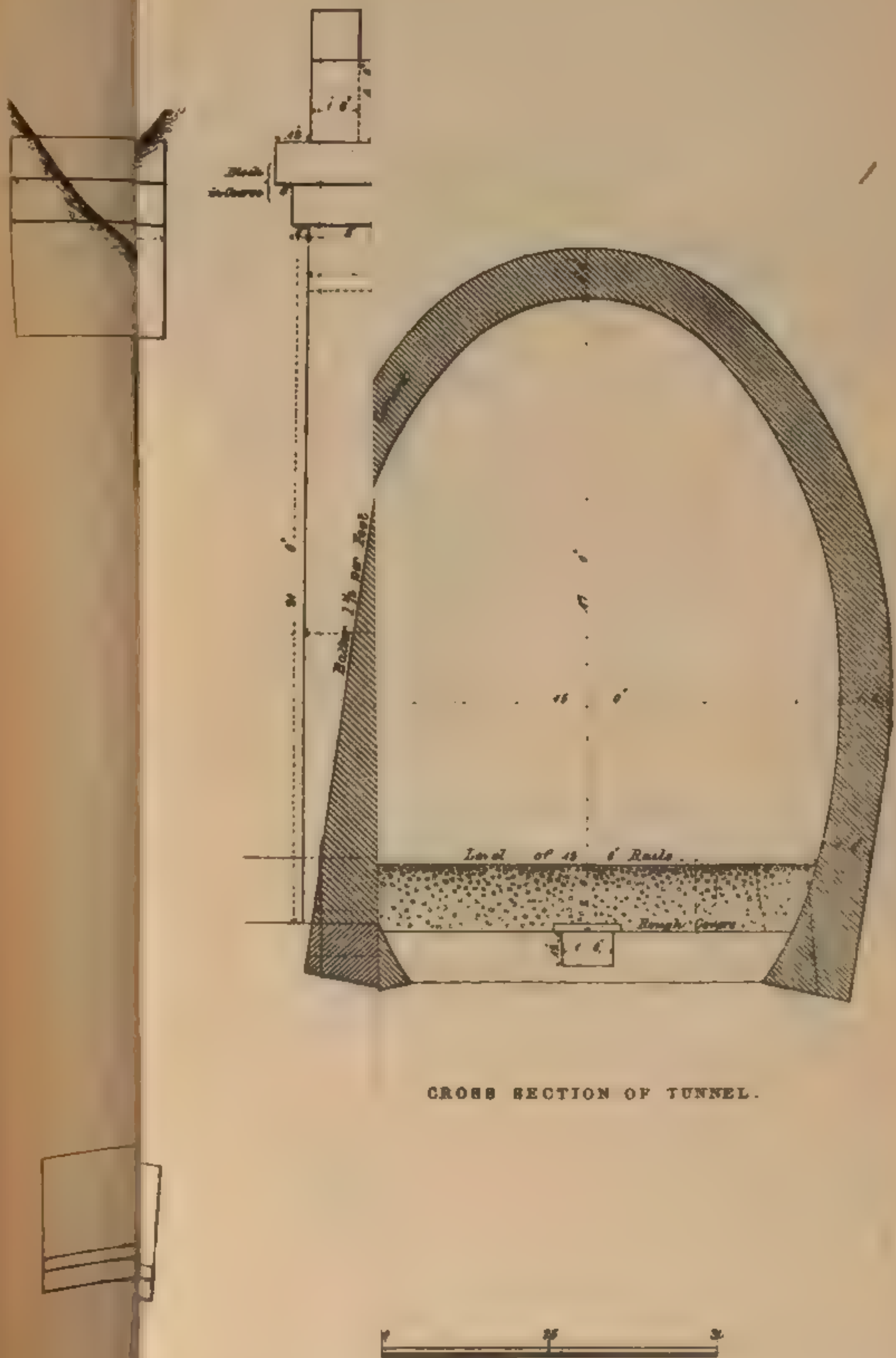
PLATE XV



CROSS SECTION OF TUNNEL.

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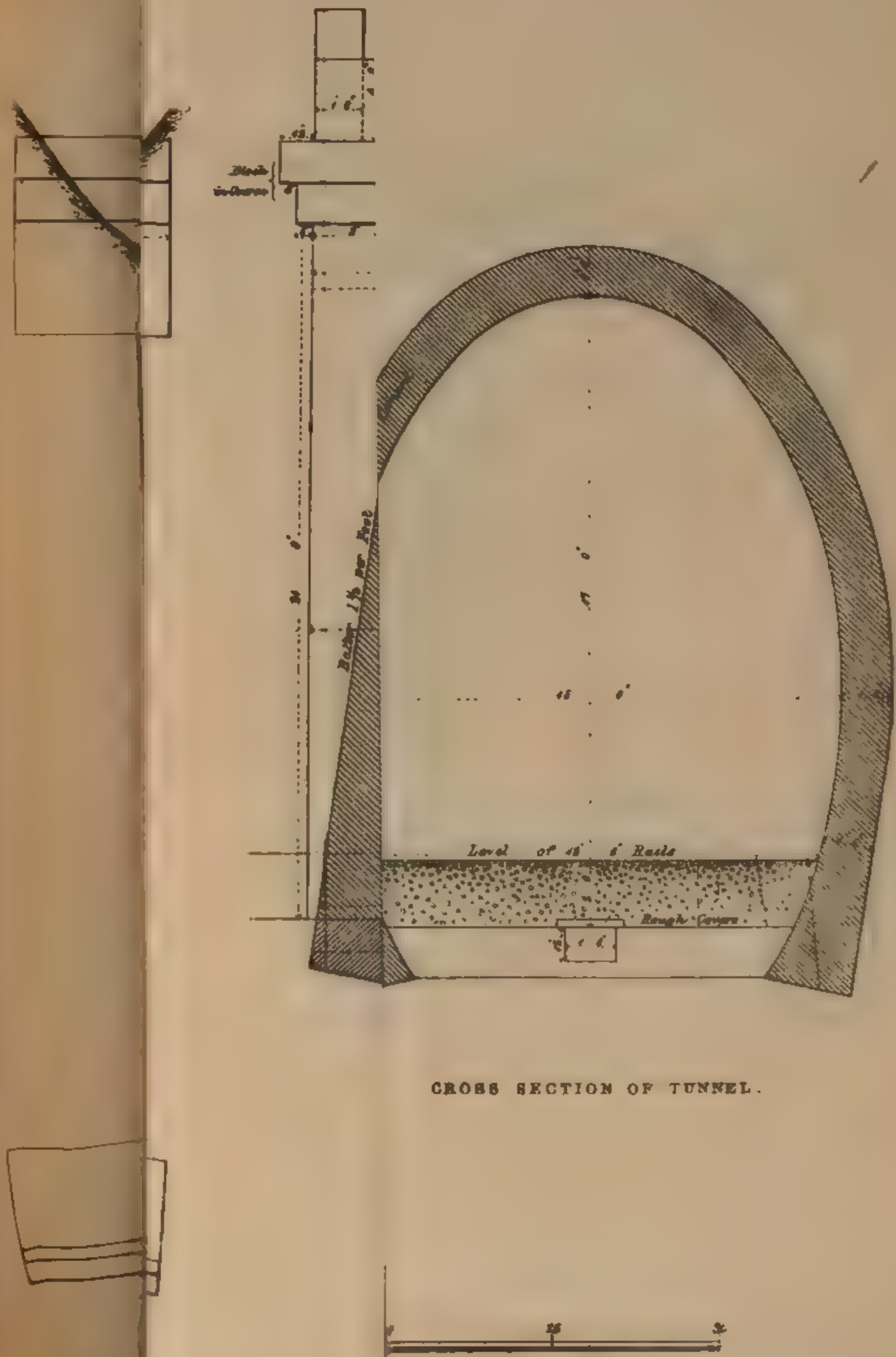
PLATE XV



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ADDITIONAL CHAPTERS

ON

THE MORE RECENT PRACTICE

OF

TUNNELLING

BY D. KINNEAR CLARK, C.E.

CHAPTER XVI.

THE DRIVING OF TUNNELS.

Two systems of driving tunnels are recognised on the Continent—the English or the German system, and the Belgian or the French system. On the English system, so-called, the main heading is opened and driven at the level of the floor or of the invert of the tunnel, and the excavation of the tunnel is completed upwards and laterally. On the Belgian system, so-called, the main heading is opened and driven through the upper part of the tunnel, at such a level that the roof of the heading is level with and forms a portion of the roof of the excavation for the tunnel, whence the excavation is extended downwards. On this system, the arch is constructed before the walls.

In short, the bottom heading is said to be the basis of the English system; the top heading, of the Belgian.

This distinction, if there ever was a reasonable foundation for it, has long ceased to exist. The mode of driving headings and excavating tunnels, as well as the order of excavation of the driving, are regulated by circumstances. The Blechingley and Saltwood Tunnels, it has been seen, were commenced with a bottom heading, which was driven through from end to end, and was used for levelling and ranging the work, before the widening out of the tunnel was far advanced. The system of the bottom heading was followed in 1833 in the construction of one or more of the tunnels on the London and Birmingham Railway. 'A tunnel of a mile long was a serious undertaking for the engineering practice of that day; and a costly, and, as it proved, an unnecessary method was adopted for ensuring the accuracy of the direction of the human moles. The line through the tunnel was straight, and had been

set out and pegged over the surface, as in other portions of the route. At every furlong in length a shaft had been sunk, with the intention of opening a driftway (a small heading) from end to end, and thus running both line and level through underground before commencing the main excavation and lining of the tunnel, which it was intended to carry on through three of these shafts, properly enlarged, using the others for ventilation. So far nothing could be better. But concurrently with this orderly arrangement of the miners came the over-careful science of the engineers. Three small observatories were erected at equal distances on the centre line, and a solid brick pillar, detached from the wooden floor and staircase, which divided the interior of the observatory into stages, was built in each. A telegraph was attached to the roof, and a highly-finished and accurate transit instrument was erected to do duty in the wood pierced by the tunnel, and to check the lines dropped down the shafts to give the direction below. While the men of science rose in the air above, the practised northern miners bored below; the driftway was carried on from eight shafts at once. When the heading was completed, the chief difficulty in ranging the line arose from the draught through it. A week after the completing the headway—which week had been spent in knocking off elbows here, raising the roof there, and lowering the floor at another place—the pupil of the sub-engineer, the only one of the staff left on his legs, had the extreme satisfaction of viewing the red signal lamp, fixed at the north end of the headway, from the southern extremity, over a regular and exact line of candles, one close to each shaft.'[1]

The bottom heading, no doubt, was, in the early English practice of tunnelling, systematically employed—not only because it served as a drain for water, but also as a means of ensuring accuracy in the levels and ranging or setting out of the work. The tunnels constructed on the Great Western Railway between Bath and Bristol, in 1842–43, were commenced by the driving of a bottom heading from end to end before the enlargement was commenced. These tunnels were constructed through hard grey sandstone, and the work of enlargement from the bottom heading was found to be costly and troublesome, more particularly as the excavated material was

[1] *Personal Recollections of English Engineers*, p. 19.

removed through the heading. There was the greatest difficulty in keeping the thoroughfare clear. The material in course of excavation fell on the road, and if it was not immediately removed it delayed the whole of the work of the tunnel by interrupting the circulation of the waggons. Where lining was to be applied to the tunnels, top headings were driven; and when the excavation for a length was completed, the lining was commenced.

In more recent practice, the bottom heading has not necessarily been constructed either for purposes of drainage or for setting out. The tunnel-aqueducts of the Glasgow Waterworks were constructed without headings. They were cut at once to the full section, 8 feet by 8 feet. In boring one tunnel, 2,325 yards long, twelve shafts were sunk from the surface, varying in depth, some of them 160 yards deep. The twenty-four faces were cut simultaneously, and all the 'junctions' were exact. Again, in the construction of the Netherton Tunnel in 1856–58, the system of bottom heading, it is true, was employed, headings having been driven both ways from the bases of 17 shafts, on the model of Simms' practice; but, as a matter of fact, the enlarging and lining of the tunnel were in course of execution at each shaft before the headings were joined up; and, so successfully had the setting out been effected, independently of the bottom heading, that no part of the tunnel diverged so much as one inch out of the direct line. It may be added that since the tunnel, destined to form a portion of a canal, was of necessity on a level, a thorough bottom heading, if made, would have been useless for purposes of drainage. Besides, the means of exhausting inflowing water by the way of the shafts is, in all but exceptional cases, amply sufficient for clearing the works of water. Exceptional cases arose in the construction of the Saltwood and Buckhorn Weston Tunnels.

The Buckhorn Weston Tunnel, 739 yards long, was constructed in 1859–60, through Kimmeridge Clay, on an incline. It was originally intended to sink only two shafts, and to utilise the incline to drain the tunnel, by means of a bottom heading driven from the lower end, through which the excavated stuff was to be conveyed. The heading was driven for a length of 200 yards, but it became so much contracted by the swelling of the sides that it was abandoned as a thoroughfare for water and waggons. The number of

shafts was increased to five, top headings were driven from each shaft, and the tunnel enlarged, timbered, and lined, as in the Blechingley Tunnel. In the course of excavation, however, veins of loose, rubbly rock were cut, from which large quantities of water were discharged, chiefly through the crown of the excavation. To check this inconvenient flow, a counter-heading was driven from the end of the ridge, over the tunnel, for a distance of ten yards beyond the intersection of the vein, in which the top water was intercepted and drained off to the face. Here, instead of a bottom heading, a top heading was employed for drainage.

Whilst the common practice of sinking shafts and multiplying the number of faces, possesses many advantages wherever expedition is an important element in the construction of a tunnel, the system is occasionally followed, according to which a bottom heading is driven from the end, at or near the formation-level, and a 'break-up' is formed at intervals upon the heading. The break-up is a substitute for the excavation otherwise formed below the ordinary shaft, and the heading is equivalent in its functions to the shaft, constituting the means of communication between the working faces and the surface. But it is easily understood that the employment of a single opening for the service of a number of faces, cannot afford the facilities of free communication offered by several shafts sunk direct upon the tunnel, at 200 yards apart, each of which is devoted to one pair of faces. The objections practically are similar in kind to those which were experienced in the construction of tunnels on the Great Western Railway, already mentioned (page 190).

Moreover, bottom headings cannot be commenced until the cuttings, or their gullets, are run up to the faces of the tunnels; and when these are cut they are not in all situations available, as the inclination of gradients may not admit of drainage.

But the greatest disadvantage of the system of bottom headings and break-ups, in certain grounds, consists in the lengthened exposure of the surface of the excavation to the action of the air, which, in clays, marls, and shales, loosens the ground; and, in rock, opens the fissures.

Finally, it may be urged as an objection to the system of working by break-up that the means of ventilation are imperfect.

There are situations, nevertheless, where a break-up may be introduced with advantage. When a bottom heading is driven from the end of the tunnel, and a break-up is formed at some distance from the end, three working faces are obtained for each end, whilst the intermediate portions are worked from shafts, in the usual way, with top headings. The Lydgate Tunnel affords an instance of this method of procedure.

Comparatively short tunnels also, under 500 or 600 yards in length, may be economically constructed on the system of break-ups—with a through bottom heading, and, say, three break-ups in the whole length. Waggons run in on a line of rails under the working faces receive the broken stuff, which falls direct into them. But in situations where foul gases are likely to be emitted, the system of break-ups is affected by the difficulty of the absence of sufficient ventilation, which may even prevent its being adopted at all.

In the history of the short tunnel, 500 feet long, on the Recife and São Francisco Railway, Pernambuco, constructed in 1856–62, an instance is afforded of the benefit that may be derived from a through bottom heading, for the transport of stores. When the small trial heading had shown that the ground was favourable, as the materials for the permanent tunnel were not at hand, and there was plenty of timber on the ground adjoining, it was decided to enlarge the heading sufficiently to take an engine through, minus the chimney. This was effected without difficulty, the enlarged heading being 9 feet 6 inches wide at the bottom, 8 feet wide at the top, and 10 feet high. A constant stream of materials passed through, during meal times, without interfering with the work. With the like objects, as soon as the end lengths had been completed in the usual manner, a surplus stock of materials was sent through, so as to last for a few days; the road was then broken up, the invert was built throughout, and the road was relaid; after which the construction of the tunnel and the supply of materials went on without interfering with one another.

The invert and arch of the tunnel were of brickwork, with side-walls of rubble masonry, and the cost was 13*s.* 6*d.* per yard for labour only.

When tunnels already constructed are to be enlarged—as, for instance, a railway tunnel constructed for a single line of rails to be enlarged for two lines—the existing tunnel, it is obvious, serves as a ready-made bottom heading, and is so employed for the construction of the larger tunnel. The Lindal Tunnel was enlarged by raising shafts through the crown of the tunnel, making a break-up at each shaft, and driving top headings both ways from the break-up.

In tunnelling through rock, top headings are now usually driven, to be worked from. For example, the Clifton Tunnel, under the Durdham Downs, was cut through mountain limestone, commencing with top headings from the shafts and a side gulley. The lower end was excavated by driving a bottom heading, from which a break-up with two faces was formed.

Other tunnels, situated near the sides of mountains, may be worked entirely from side drifts. The Shakespeare Tunnel, or, more correctly, double tunnel, driven through the Shakespeare Cliff, near Dover, consists of two narrow tunnels, carrying each one line of rails, 12 feet wide and 30 feet in extreme height, through the chalk, separated by a solid pier or wall of chalk, 10 feet thick. The chalk is of variable quality, and the greater part of the tunnel is lined with brick, strengthened by counterforts at 12-feet intervals. The tunnel is 1,430 yards in length, rising westward with an inclination of 1 in 264. The tunnel being within a short distance from the face of the cliff, the material excavated was discharged through galleries about 400 feet long, driven in from the face of the cliff, into the sea; the first operation having been to run a bench or roadway along the face of the cliff. There are seven shafts, averaging 180 feet deep.

From the foregoing instances, which are but types of many others, it may be inferred that there is no specifically English system—top and bottom headings are used just as circumstances may direct. Mr. Simms was evidently impressed with the necessity for through bottom headings; but it has been amply proved by more recent experience that they are not necessary, either for the purpose of effecting an exact setting out, or for the

purpose of drainage. With respect to the means of setting out a tunnel, it may suffice to mention that the Mont Cenis Tunnel, upwards of 6 miles in length, was set out, of course with the aid of a through heading, entering from the ends; the junction was effected without any error horizontally, and with only a foot of divergence vertically. And as to means of drainage, tunnels may, in most cases, be drained, by means of steam power, through shafts; whilst tunnels like that of Mont Cenis, where shafts or side drifts cannot be applied, are constructed on inclines, which rise from each end, and meet at a summit in the interior, and so afford a fall for natural drainage.

In the excavation of tunnels of great length, and through mountains of great elevation—as, for instance, the tunnels through Mont Cenis and the St. Gothard, where, in the absence of shafts, the only means of approach are from the ends—it is manifest that the proper method of penetrating the mountain is the method of the top heading, with subsequent enlargement. The excavation of the Mont Cenis Tunnel, it is true, was commenced by means of a bottom heading, from which the enlargement was effected upwards and laterally; but the system of the bottom heading has been completely negatived in the construction of the St. Gothard Tunnel, in which the top headings or advanced galleries have been driven from the commencement, and continue to be exclusively followed in the excavation of the tunnel, both in the solid rock at the north end, and in the loose, uncertain, and watery strata of the south end. Drainage is more easily effected in rock by the method of the top heading, whilst also ventilation—a matter of importance in long tunnels—is more conveniently and effectively performed.

From what has been said, it may be inferred that in the construction of tunnels the masons or bricklayers should commence the lining as soon as possible after the excavation is prepared for receiving the masonry.

CHAPTER XVII.

CASUALTIES IN TUNNELLING.

CASUALTIES in tunnelling arise chiefly from the presence of water, quicksands, or treacherous material; and they have been incidentally noticed in the preceding discussions.

The difficulties experienced in constructing some tunnelling through chalk and greensand under a head of water at Holywell, on the Wilts and Somerset Railway, were similar in character to those at Saltwood Tunnel, which have been described by Mr. Simms. It was intended that the tunnel on that railway should have been constructed by sinking shafts, and connecting them by a bottom heading, mining through between open cuttings at the north and south ends; but the indications from the borings of the ground were unfavourable, the body of the tunnel being in chalk, full of faults, whilst the cuttings at both ends were in greensand, and copious springs showed themselves along the line of operations, which were conducted through strata generally dislocated and untrustworthy. In sinking the shafts, the water brought away with it such quantities of sand as to create cavities around, and cause serious failures in, the timbering, which required to be renewed and replaced several times. Gullets were cut at lower levels, in hopes of their drawing off the water, but the tenacity of the soil and the numerous faults prevented their being useful. By incessant pumping the water was cleared, but the framing of the shaft sunk bodily, and was only retained by a hanging curb and rods from the surface. The quantity of water increased so much that the briefest delay in pumping obliged the men to leave the headings. At length it was observed that the dip of the sand-rock, which was the water-bearing stratum, was favourable for conducting away the water, if tapped at the lower level. This was done, and the result

was successful. In the subsequent extension of the open cuttings, the numerous vertical faults were shown to have been, in a great degree, the cause of the slips in the shafts. It was next determined to try the effect of a syphon, formed of cast iron pipes 6 inches in diameter: the short leg dipped into a sump at the bottom of one of the shafts, whilst the longer leg extended through the crown heading and terminated in a cistern in the north cutting. The air having been exhausted by means of a hand-pump at the summit of the bend, the action was so perfect as to drain the blocks of sand and enable the headings to be completed.

Mr. Simms mentions (page 22) that, for the purpose of getting rid of the water that flowed into the Saltwood Tunnel, an adit was driven through the side of the open cutting at the lower end of the tunnel, to afford an outflow towards the natural drainage of the country. In this instance the through bottom headings did good service in conducting away the water

The construction of the Kilsby Tunnel, on the London and Birmingham Railway (2,398 yards long), was let for the sum of 99,000*l.*, or about 40*l.* per lineal yard. Its actual cost amounted to nearly 300,000*l.*, or 125*l.* per yard. The excessive extra cost arose from the presence of a quicksand which was intersected, and which had been missed in the trial-borings, though it extended over a length of 450 yards of the tunnel. Expensive pumping machinery was set up and worked in order to drain the sand, lifting 2,000 gallons per minute, for a period of nine months. The brickwork is mostly of a thickness of 27 inches, and was built either in Roman or in metallic cement. The length of the tunnel is divided by two ventilating shafts, 60 feet in diameter, which are 3 feet thick, of brickwork. The shafts were built from the top downwards, by excavating for small portions at a time, from 6 to 12 feet in length and 10 feet deep.

The Box Tunnel, on the Great Western Railway, is 3,123 yards in length. It intersects oolite rock, forest marble, and lias marl. Eleven principal shafts, 25 feet in diameter, and four intermediate shafts, 12 feet 6 inches, were sunk, for the purpose of carrying on the works of the tunnel; they averaged 200 yards apart. The normal section of the tunnel is 27 feet 6 inches at the springing of the invert, and 30 feet wide at a height of

7 feet 3 inches above the springing; the height of the soffit above the rails is 25 feet. Where brickwork is used, the sides are seven rings of half-brick in thickness, the arch six rings, and the invert four rings. The constant flow of water into the works from the numerous fissures in the rock required the use of pumping machinery on an extensive scale. From November 1837 to July 1838 the works were suspended, as the water gained on the steam-pump employed, filling up the portion of the tunnel then completed, and rising to a height of 56 feet in the shafts. A second pump, worked by a 50 horse-power engine, was applied, and the water was so far reduced that the works could be resumed. When another irruption took place, the water was pumped out at the rate of 32,000 hogsheads a day.

But, in the experience of the construction of the St. Gothard Tunnel through the Alps, the discharge of water arrived at something far beyond the experience of ordinary tunnelling. Springs and cascades of water, sufficient to knock down a man, sprang from holes and fissures in the rock of the southern excavation, the united volume of which gave a discharge amounting to upwards of 3,000 gallons per minute, or 80,000 hogsheads per day. The miners occasionally worked knee-deep in water; and, without the indispensable aid of mechanical perforators, it may be asserted that the St. Gothard Tunnel would have been impossible of execution.

Great danger arises in certain soils from slips. In the construction of the Fareham Tunnel, on the Gosport line, a fall of the superincumbent earth carried away 40 yards in length of the brick arching, though it was of unusual thickness, being 3 feet thick. Recently, a mountain-slip took place on the Salzburg-Tirolce Railway, carrying away 120 yards of the tunnel through the Unterstein, a spur of the Bichloch mountain. Seventy years ago the Embach spur, on the opposite side of the river, slipped from natural causes; now the Unterstein, of the same formation, has slipped from disturbance by the tunnel. Here it would have been better engineering to have directed the tunnel through the solid stem of the Bichloch, even though at greater expense than was laid out on the tunnel as executed. The Unterstein is a mass of loose slate, and has been slipping away bodily, with a height of 160 yards, from the parent rock, at the rate of a metre per day.

The tunnel was solidly built of stone arching, one metre in thickness, and the side walls in proportion. Six weeks before the final catastrophe the tunnel gave signs of disturbance.

The Santiago and Valparaiso Railway passes through a spur of the Andes by a tunnel 1,600 feet long, which passes for two-thirds of its length through granite and trap-rock, containing much water; the remaining third passing through decomposed rock and clay. The progress of the works was suspended for various reasons; and when the work was resumed, a slip was occasioned by the decay of the timbering under the wet decomposed rock, which took place during the suspension of the works. When the works were resumed, the material descended into the tunnel as fast as it could be removed, in spite of every attempt to restrain it, until the surface of the ground, at a height of 120 feet above the tunnel, began to sink. When it had sunk about 10 feet, a large frame of timber was constructed in latticework, strongly bolted together, and deposited on the surface above the aperture; brushwood was thickly laid on the frame, and the excavation below was then proceeded with. The frame rapidly disappeared, the sides of the cavity above falling in as it descended. After the lapse of a short time, a second frame, covered with brushwood, was deposited on the surface; and almost immediately afterwards the miners below began to gain upon the slip, and at length were enabled properly to insert the timbering. It was discovered, in doing so, that the first frame had descended to the tunnel, and had perfectly plugged up the aperture.

From the two immediately preceding cases of slips in tunnels a lesson may be derived, and may be summed up in the following words: Beware of the spurs of mountains. The Clifton Tunnel, under the Durdham Downs, was driven under the slope of the upper portion of the Downs which face the Avon. Fortunately, it was placed at a level below the plane of cleavage, and it passes through rock, which was undisturbed by the slip.

In the Watford Tunnel, which passes through the upper chalk formation, where it is covered with a thick irregular bed of gravel, the chalk was deeply fissured, sometimes to a hundred feet in depth, the fissure being filled with gravel, which, when worked into, 'rushed down with such violence as

to plough the sides of the tunnel as if bullets had been shot against it.' In such an accident, occurring at the foot of one of the working shafts, ten men who were then at work were overwhelmed. The accident led to the construction of the large ventilating shaft near the centre of the tunnel, which occupies the side of the cavity.

The pressure of clay and shale, when disturbed by excavation, is in some situations something almost immeasurable. The phenomena of disturbance supply powerful examples of the flow of solids. There is the familiar phenomenon of the bending and snapping of huge poles and strongly-timbered frames by the moving pressure of clay. In the construction of the Primrose Hill Tunnel, through the London clay, the lengths were limited to 9 feet, and strongly timbered, till the arching was completed. In virtue of its mobility, however, the moist clay exerted so great a pressure on the brickwork as to squeeze the mortar from the joints, to bring the inner edges of the bricks into contact, to grind them to dust by degrees, and to reduce the dimensions of the tunnel slowly but irresistibly. The evil was counteracted by using very hard bricks, laid in Roman cement, which, setting before the back pressure accumulated, hardened and resisted the pressure, and so saved the bricks. The thickness of the brickwork was augmented, almost throughout the tunnel, to 27 inches.

A similar accident occurred to a portion of the invert of the Netherton Tunnel, built on a foundation of 'blue-bind' or marl. Some weeks after it was built the invert was forced up in several places by the swelling of the ground, and at one point the bricks were crushed almost to powder. The invert was rebuilt with a greater versed sine.

For the reason that the surrounding ground has been disturbed and moved in the course of the construction of tunnels through clay, shale, or loose strata, the operation of the enlargement of tunnels is peculiarly hazardous. Unexpected spaces may be met with, full of water, or mud, or masses of ruptured rock. The account of the enlargement of the Lindal Tunnel, at a subsequent page, gives examples of such casualties.

It is known, too, that the pressure on tunnels in comparatively shallow ground, say, less than 40 feet below the surface, may be localised and con-

centrated upon the crown of the arch with peculiar severity. Mr. Simms accounts for the greater pressure upon the work in shallow ground by the supposition that the whole superincumbent mass acts vertically downwards, whilst at greater depths it is more or less sustained as an arch over the tunnel, which is proportionally relieved of the pressure. In the building of the Stapleton Tunnel, the arch was at first built with only four rings of brickwork in mortar. When the autumnal rains set in, the ground began to press heavily; so much so that the line of the tunnel could be traced as a hollow on the surface of the ground, which was not more that 40 feet above the tunnel. A portion of the tunnel fell in, and was rebuilt with five and six rings of brick.

An accident of the same nature occurred to the Ménilmontant Tunnel on the Chemin de Fer de Ceinture, near Paris. A portion of the tunnel which passes under the cemetery of Père la Chaise sank down, making a void in the cemetery 11 yards long by 6½ yards wide, and carrying thirty-four tombs into the opening.

CHAPTER XVIII.

TUNNELLING IN CLAY, MARL, ETC.—BUCKHORN WESTON TUNNEL, ON THE SALISBURY AND YEOVIL RAILWAY.

THE Buckhorn Weston Tunnel, for which Messrs. Locke & Errington were the Engineers, was constructed under the superintendence of Mr. J. G. Fraser. It was constructed through Kimmeridge clay, intersected with veins of loose rubbly rock, as shown in the general section, Plate XVII. These veins acted as conduits for a large quantity of water, which flowed into the tunnel at the rate of 90 gallons per minute, for nearly half its length. The principal influx of water proceeded from the vein of 'loose rock and water,' and was confined to the crown, instead of a general shedding. It was eventually remedied by driving a heading, 5 feet square, for 200 yards in length, above the tunnel, and about 10 yards beyond it, as shown in the section. A 12-inch pipe was laid in the heading and filled round with loose stones. The water, thus intercepted, was carried away from the work. The width of the tunnel is 24 feet 6 inches at the level of the rails, widened out to 25 feet at 3 feet above. The height is 20 feet above the rails. The crown of the arch is more pointed than that of the Lydgate Tunnel. The length of the tunnel is 739 yards. The tunnel was completed in February 1863, and was constructed in seventeen months.

It was originally intended, in executing this tunnel, to sink only two shafts, and to form a bottom heading for waggons from the cutting at the east end, the gradient falling in that direction, so that drainage could have been obtained. This heading was driven for 200 yards, when the action of the atmosphere caused the sides to bulge so much that double timbering had to be resorted to. This failed to check the swelling, the plan was abandoned, and a smaller heading was substituted. The waggons were

consequently prevented from entering the tunnel, and three additional shafts, making five in all, had to be sunk. They were not intended to be permanent, and the sides were only timbered, but very strongly, on account of the treacherous nature of the ground. These shafts were 8 feet square, clear. The earth was raised by means of horse-gins.

Top headings were driven from each shaft. They furnished the faces, from which 645 lineal yards were worked, averaging 56 yards per month. A break-up was established at a distance from the east end, and the break-up and end gave three additional faces, from which 94 lineal yards were worked, equal to 10½ yards per month. The lengths mined in detail are given as follows:- -

BUCKHORN WESTON TUNNEL.

Lengths Mined from the Shafts and Ends.

No. of Shaft.	Lengths driven.		Total.	Time occupied.	Rate per month.
	East.	West.			
	Lineal yards.	Lineal yards.	Lineal yards.		Lineal yards.
1	63	45	108	1858 Oct. to 1860 Jan. .	7½
2	64	88	152	„ „ „ Feb. .	9½
2*a*	29	29	58	1859 July „ Jan. .	10½
3	89	106	195	1859 Sept. to 1860 Feb. .	12
4	70	62	132	1859 July „ „ .	16½
Break-up.	—	—	73	„ „ „ „ .	10½
Face. .	—	—	21	„ Oct. to 1859 Dec. .	10½
Total. .	—	—	739		77

The lengths varied from 10 feet 6 inches, in heavy ground, to 15 feet in favourable ground. The bars were of larch, of large scantling, the crown bars being 18 inches in diameter, and fixed about 18 inches apart (see sections). The centres were strongly braced, each rib containing 35 cubic feet of timber, and 285 lbs. of wrought iron in bolts and straps. They were fixed at about 4 feet apart.

As side pressure was anticipated at the commencement of the work, the first ten lengths were built with an invert 18 inches thick, which contained 4 cubic yards of brickwork per lineal yard (see section). Further experience

and a more accurate knowledge of the material, justified the abandonment of the invert. The pressure at the crown of the tunnel, occasioned by the water, on the contrary, rendered it necessary to construct a length of 390 lineal yards, with seven rings of brickwork, or 32 inches of thickness. The remaining length of 350 lineal yards was favourable, the water-line having dipped gradually, as shown on the longitudinal section, and it was constructed with six rings of brickwork, or 27 inches of thickness. Great caution was exercised in packing behind the brickwork, to prevent subsequent settlement upon it. Many of the bars were built in; three on an average were left in the heavy ground.

The tunnel was built throughout of brickwork; upwards of six millions of bricks were used. Sharp sand was not found in the neighbourhood, and, as a substitute, burnt clay, fine sand found in the locality, and broken bricks were ground together, and mixed with Bridgwater hydraulic lime, in the proportion of 2 to 1. The result was perfectly successful.

The following table gives the length of each thickness built:—

BUCKHORN WESTON TUNNEL.

Thickness and quantity of Masonry, with Earthwork.

Length.	Thickness of work.	Earthwork per lineal yard.	Masonry, per lineal yard.	Total Masonry.
Lineal yards.	Ft. In.	Cubic yards.	Cubic yards.	Cubic yards.
4	3 5	110	27·25	109
41⅓	2 8	95	24·38	1,008
	With invert.			
335⅔	2 8	85	20·56	6,903
178⅓	2 3	80	18·22	3,250
178½	2 0	77	14·88	2,657
737⅚				13,927
Average per lineal yard .		80	19	

The first length was keyed in October 1858, and the last in February 1860.

After the completion of the work, water continued to flow. It was conveyed by pipes into the regular channels. The discharge at the completion

of the works was gauged, when it was found not to have abated since the time it was tapped eighteen months previously.

The cost of the shafts amounted to 2*l.* 5*s.* per lineal yard of tunnel.

The average price for mining and tipping was 4*s.* 6*d.* per cubic yard. The average cost of mining was 30*l.* per lineal yard, exclusive of shafting. It consisted of the following items:—

	£	s.	d.
Mining and tipping	18	0	0
Headings	2	0	0
Timber and iron and steel	7	15	0
Powder and grease	1	9	0
Management	1	0	0
Total per lineal yard	30	0	0

The cost of setting the centres came to 6*s.* per lineal yard of tunnel.

The total cost of the tunnel was 53,000*l.*, or 72*l.* per lineal yard, of which detailed particulars are subjoined:—

BUCKHORN WESTON TUNNEL—PARTICULARS OF COST.

Description.	Total cost.	Cost per lineal yard of Tunnel.	Cost per cubic yard.
	£	£ s. d.	s. d.
Mining and tipping	13,300	18 0 0	4 6
Headings and shafts	3,070	4 5 0	—
Timber	3,400	4 15 0	—
Iron and steel	2,250	3 0 0	—
Powder and grease	1,040	1 9 0	4 4¼
Horsework	4,300	5 16 0	—
Bricks, coal, and sand	13,650	18 10 0	18 6
Lime and sand	1,732	2 7 0	2 4
Bricklaying	6,003	8 0 0	8 0
Setting centres	225	0 6 0	0 3½
Temporary roads and buildings	1,095	1 10 0	—
Management and plant	2,650	3 10 0	5 per cent.
Face and drain	400	0 10 0	—
Totals	53,115	71 18 0	—

Sir Arthur Helps, in his 'Life of Mr. Brassey,' mentions that the cost of construction of this tunnel varied extremely for different parts. The construction of a yard at one end cost 12*l.*; whilst a yard at the other end cost as much as 120*l.*

CHAPTER XIX.

TUNNELLING THROUGH COAL-MEASURES—THE LYDGATE TUNNEL, ON THE LONDON AND NORTH-WESTERN RAILWAY (OLDHAM BRANCH).

THE Lydgate Tunnel was constructed under the superintendence of Mr. J. G. Fraser, acting for Messrs. Locke & Errington, the Engineers to the Railway. It was driven through the coal-measures. Two sections of the tunnel, in shale, and in rock, are given in Plate XVII. Faults are common in this formation, and several were met with in the course of the work. One of these presented itself in a singular manner, one-half of the tunnel being in strong shale and rock in veins, whilst the other half was in a mass of wet and loose shale. The tunnel is 25 feet wide, with parallel sides, up to 3 feet above the level of the rails; the height to the soffit is 20 feet, and the castings average 3 feet 6 inches below the rails. The total length of the tunnel is 1,332 yards, or three-quarters of a mile, of which about 1,000 yards is on a straight line, and the remainder on a curve of 74 chains radius. The following are the lengths of the different strata cut through:—

	Lineal yards.
Clay and loose shale	210
Strong shale	335
Strong shale, interspersed with bands of rock	474
Rock, with veins of shale	135
Rock	130
Limestone	13
Fireclay	30
Coal	5
Total length	1,332

The work was commenced in August 1854, and completed in March 1856, over a period of seventeen months.

Five shafts, 9 feet diameter in the clear, were sunk in the usual manner,

excavating through soft material, and drilling and blasting through rock. After attaining the average depth of 60 feet, the material was raised by steam power. Four shafts, about 230 yards apart, were permanent for ventilation. No. 1*a* had formerly been a colliery shaft, and had not been used for many years. It was reopened by the contractor, and a cross heading was driven from it into the tunnel, the centre of which was 40 feet distant. The permanent shafts were lined with 9-inch brickwork, or 12 inches of masonry, except where in rock; they were finished at the soffit of the tunnel with ashlar curbs 2 feet 3 inches deep. Where water penetrated, iron shields, with a gutter round the edge, were suspended, and the water conveyed by a pipe down the side of the tunnel, into the regular channels. The shafts were carried 12 feet above the surface of the ground, and were completed with an ashlar coping. A 9-horse power steam engine was fixed at shaft No. 1*a*, a locomotive engine between shafts Nos. 1 and 2, to work them both, and another locomotive between shafts 3 and 4.

The shafts were all commenced in August 1854, and completed to the respective depths measured to the formation-level hereunder stated:—

			Depth.	Rate per month.
No. 1*a*	completed	October 1854	27⅓ yards	—
1	,,	November 1854	53⅓ ,,	13 yards.
2	,,	February 1855	80 ,,	13 ,,
3	,,	,, ,,	75⅔ ,,	12½ ,,
4	,,	January 1855	53 ,,	5 ,,
Total depth			289⅓ ,,	43½ ,,
Average depth of each			58 ,,	

Much inconvenience arising from foul air was checked by the proximity of the shafts. Foul air was driven away by means of fans fixed on the surface, which forced down a volume of air through pipes, which were fastened along the tunnel. In the neighbourhood of the old coal-workings, which ran across the tunnel, much choke-damp was met with, which was counteracted by a current of fresh air forced down through a bore-hole from the surface, lined with an iron pipe.

Great care had to be exercised in fixing the centres througn tne portion

of the tunnel lined from the heading of No. 1*a* shaft, 245 lineal yards in extent, as part was on a curve and part on a straight line.

The faces walled from the cuttings at the ends, for 141 yards in length, were mined with a bottom heading, and at a distance of 30 or 40 yards from each end a break-up was made, from which lengths were driven both ways, towards the open cutting, and towards the next shaft. The remainder of the tunnel, worked from the shafts, was mined by a top heading 6½ feet high by 4½ feet wide. The shafts furnished ten faces; and 1,191 lineal yards out of the total length were worked from them, each face averaging 17·26 lineal yards per month. The open ends gave four faces in the break-ups, each making 9 lineal yards per month. The lengths mined from the different shafts are given in the following table:—

LYDGATE TUNNEL—LENGTHS MINED FROM THE SHAFTS AND ENDS.

No. of Shaft.	Lengths driven.		Total.	Time occupied.	Rate per month.
	East.	West.			
	Lineal yards.	Lineal yards.	Lineal yards.		Lineal yards.
1*a*	138	107	245	1854, Oct. to 1856, March.	15
1	157	126	283	„ Dec. „ „	19
2	100	96	196	1855, March „ „	16
3	95	108	203	„ „ „ „	17
4	119	145	264	„ Feb. „ „	19
Ends.	95	46	141	„ Oct. „ „	9
Total.	—	—	1,332		95

The excavation was conducted in the usual manner—the rock and strong shale being blasted out, and the clay and loose shale axed out. As each length was headed it was widened out, and the roof and sides supported by larch bars and poling-boards, from 9 to 10 feet above the formation level. The material was removed in iron skips, capable of holding half a cubic yard each, which were placed on light trollies, and these pushed along tramways laid between the work and the shafts, raised to the surface by engine power, and tipped on the spoil-bank. The lengths mined averaged—in loose shale, 12 feet; strong shale, 15 feet; rock, 24 feet, in some instances 30 feet.

The centres consisted of skeleton ribs placed about 4 feet apart; at the leading end, two centres were placed close together, for greater security.

The side walls were built of coursed rubble, the beds of the stones being punched with a hammer. The footings were not less than 18 inches below the formation-level, and the walls were carried 7 feet 3 inches above the level of the rails. The arch, for 632 lineal yards, was turned with fitted rubble; and from the scarcity of good bedded stone, 700 yards were of brickwork. The mortar was composed of barrow-stone lime mixed with coal ashes, in the proportion of 2 to 1, ground by heavy iron rollers, and used fresh. Its setting power was most satisfactory.

Where the crown bars sagged much, they were built in, the intermediate spaces being filled with brickwork. Where water was met with over the crown of the arch, the tunnel was covered with zinc, terminating in a gutter to convey the water where a pipe was built through the masonry, to be discharged into the drains.

There was considerable variation in the thickness of the masonry. It was:—

	Sides.	Arch.
In shale .	2 feet 6 inches thick .	2 feet thick.
In rock .	1 foot 9 " " .	1 foot 6 inches thick.

The following table gives the lengths of each thickness built:—

LYDGATE TUNNEL.

Thickness and Quantity of Masonry, with Earthwork.

Length.	Thickness.		Earthwork per lineal yard.	Masonry, per lineal yard.	Total Masonry.
	Sides.	Arch.			
Lineal yards.	Ft. In.	Ft. In.	Cubic yards.	Cubic yards.	Cubic yards.
10	3 6	2 6	84	20	200
30	2 9	2 6	82	$18\frac{1}{4}$	547
16	2 6	2 6	81	$17\frac{1}{2}$	280
30	2 6	2 3	$79\frac{1}{2}$	$16\frac{1}{3}$	490
120	2 6	2 0	78	$15\frac{3}{4}$	1,890
119	2 0	2 0	76	$14\frac{1}{2}$	1,725
62	2 0	1 9	74	$13\frac{1}{3}$	827
24	2 0	1 6	$72\frac{1}{2}$	$11\frac{3}{4}$	282
500	1 9	1 6	71	$11\frac{1}{3}$	5,667
421	1 6	1 6	70	$10\frac{3}{4}$	4,526
1,332	—	—	—	—	16,434
Average, per lineal yard .		—	—	—	$12\frac{1}{3}$

The contract price for excavation, without distinction, was 4*s.* 6*d.* per cubic yard, including all the timbering. The prices paid to the miners varied from 8*l.* to 18*l.* per lineal yard, according to the material; nearly half the total length of the tunnel amounting to 12*l.* per lineal yard, or less.

The price for setting the centres was 8*s.* per rib.

The time the masons and labourers were allowed for building, with the cost, was as follows:—

			£	s.	d.
Side walls, 2 feet 6 inches thick, and 12 feet in length—					
4 Masons, 1¾ shift of 8 hours . .	= 7	at 5*s.* 6*d.*	1	18	6
9 Labourers	= 15¾	at 3*s.* 6*d.*	2	15	1½
Arch, 2 feet thick and 12 feet in length—					
4 Masons, 3 shifts	= 12				
2 do. extra for key, 1 shift . .	= 2				
	14	at 5*s.* 6*d.*	3	17	0
11 Labourers, 3 shifts	= 33				
3 do. for key, 1 shift	= 3				
	36	at 3*s.* 6*d.*	6	6	0
Total (about 4*s.* 9*d.* per cubic yard) . . .			14	16	7½

The contract price for the tunnel through rock was 26*l.* per lineal yard, and through shale 35*l.* 16*s.* per lineal yard; the average price was 30*l.* per lineal yard.

NETHERTON TUNNEL, SOUTH STAFFORDSHIRE, ON THE BIRMINGHAM CANAL.

The Netherton Tunnel forms a portion of the section of canal from Netherton to Dudley Port, designed by Messrs. Walker, Burgess, & Cooper, and was constructed under Mr. J. R. Walker, as Resident Engineer, in 1856–58. The time occupied in the construction of the tunnel, from the commencement of sinking the first shaft to the laying of the last brick, was two years and seven months.

The tunnel passes under 'Rowley Rag,' a mass of trap-rock. It is 3,036 yards, or nearly 1¾ miles long, 27 feet wide, and 24 feet 4 inches high in the clear. The water-way is 17 feet wide, 6 feet deep in the middle, and 5 feet

at the sides. The soffit of the tunnel is 15 feet 9 inches above the level of the water.

Seventeen shafts were sunk for the construction of the tunnel, placed at from 164 to 200 yards apart, and carried down to the level of the invert. Of these shafts, ten were only intended for use during construction, and seven were to be left open for ventilation. Four of the temporary shafts were rectangular, lined with timber, 9 feet by 8 feet in the clear. The curbs were of fir timber, 11 by 10 inches in section, placed 6 feet apart, and closeboarded. The other six temporary shafts were lined with brick, and 8 feet in diameter. One of these, and the first four, were filled up afterwards. The other temporary shafts were covered with cast-iron plates, about 5 feet below the surface. The permanent shafts were lined with brickwork, 9 inches thick; one, which was worked with a horse-gin, was 10 feet in diameter, and the others were 9 feet. The brick lining was supported on the arch of the tunnel by a cast-iron curb, weighing 9 tons, in four pieces bolted together, with skewbacks to bear on the rings of the arch.

The quantity of water met with was considerable in several of the shafts; in some cases it was drawn in buckets; but at shaft No. 8, a pumping-engine of 20-horse power was kept at work. No attempt was made to 'coffer' out the water met with in the shafts. It is received in zinc gutters, nailed to the curbs, and is conducted by a cast-iron pipe fixed down the inside of the shaft, and in a groove built in the soffit of the tunnel, to the back of the towing-path, and under it into the canal.

The whole of the shafts were sunk by the ordinary method. The material having been removed to a depth varying according to the nature of the ground, an oak curb, 9 by 3 inches in section, was placed on the bottom, on which the brickwork was built. The excavation of the length below was then proceeded with, the curb being temporarily propped until underpinned by the brickwork brought up from the curb below. The brickwork was laid in mortar, in alternate header and stretcher courses, the headers being radiated. Cement was used when the ground was very wet. The total depth of all the shafts was 3,083 feet, of which 2,293 feet were lined with brickwork. The greatest depth of any shaft was 344 feet, the least depth

65 feet 9 inches, and the average depth 181 feet. The average rate of progress, from the commencement to the completion of each shaft, was 2 feet per day of 24 hours; but, counting only the actual time in which work was done, the average was 3 feet 4 inches per day. The shafts passed through marl and 'bind' principally; but coal and basalt were met with in several of the shafts.

The headings were driven in each direction from the shafts, as they were sunk. They were 3 feet wide by 5 feet high, the bottom of the heading being level with the top of the invert. Though the construction of the tunnel was proceeded with from seventeen shafts and thirty-four faces, without waiting for the completion of the heading, no part of the tunnel was so much as 1 inch out of the direct line; and, when water was admitted, the guards were found to be exactly level. But exceptional subsidences took place at three points, owing to mining operations, where the guard and towing-path walls were of course levelled up. With the exception of some apparently unconnected pieces, the only trap rock met with was a wall, or dyke, about 8 feet thick, north of shaft No. 7. To the north of the dyke, the stuff excavated was principally marl, coarse sand-rock, and a hard shaly clay, known as 'blue bind.' On the south side also, marl and bind were extensively met with; but coal, lias, ironstone, and fireclay were also passed through in several places. The tunnel was constructed on the system adopted by Mr. Simms for the Blechingley Tunnel. The lengths excavated varied from 12 to 13 feet. The material was of such a nature as to require that the arch should be closely timbered throughout. The spaces left in the excavation were filled up either by solid brickwork, or by earth rammed in.

The brickwork of the tunnel is, generally, 22½ inches thick in the walls and arch, and 13½ inches in the invert; but, in the side and shaft lengths, the walls and arch are 27 inches thick. In places, also, where the ground was bad, the thickness of the walls and the arch was increased to 27 inches, and that of the invert to 18 and 22½ inches.

The lengths of the various sections of tunnel, as built, were—

Thickness.	Thickness.	Length.
Walls and arch, 22½ inches.	Invert, 13½ inches.	2,467 yards.
„ 22½ „	„ 18 „	109 „
„ 22½ „	„ 22½ „	85 „
„ 27 „	„ 13½ „	375 „
Total length		3,036 „

Some weeks after the invert was built it was forced up in the centre, in several places, where the foundation was 'blue bind' or marl, owing to the swelling of the ground. Although the brickwork was in some parts raised 5 inches, it was not broken or crippled except at a point south of No. 7 shaft, where the invert was forced up 8 inches at the centre; here the bricks were crushed almost to powder. A length of 130 feet of invert was cut out and rebuilt, in 6-feet lengths, the side walls being carefully strutted. A portion of the invert, 49 feet long, was rebuilt with a versed sine of 2 feet 6 inches.

The brickwork of the tunnel consisted of Staffordshire brown bricks, laid in mortar; that of the side walls being built in old English bond, and that of the arch and invert in half-brick ring, with headers where two courses coincided. The skewback of the invert was built with large bricks moulded for the purpose. Five stop-sills were placed in the tunnel, and one at each end, to enable the water to be withdrawn from any part when required. The tunnel-fronts were built entirely of brickwork, with curved and battering wing walls. The face of the arch and the coping consist of large moulded Staffordshire blue bricks. Some of the coping bricks were unusually large; those on the tunnel-fronts were 27 inches by 18 inches in section. From the results of experiments on the strength of the bricks used in the tunnel, it appears that the resistance, when crushing commenced, was as follows:—

	Per square foot.
Oldhill brown bricks	115 tons.
Tividale blue bricks	89 „
Oldbury brown bricks	72 „
Dudley Port brown bricks	66 „
Oldbury brown bricks	53 „
Netherton brown bricks	53 „
Stourbridge fire bricks	96 „

The mortar was made with four parts of Hayhead lime, which is strongly hydraulic, measured before being slacked, four parts of sand, and one part of ashes, ground together. This mortar was found to set so satisfactorily that cement was not used even in the tunnel, except when the work was required to set in a few hours.

For the conveyance of materials to the shafts, a tramway of 30 inches gauge was laid over the whole length of the tunnel, with passing places and sidings at each shaft.

The trough of the canal in the tunnel was formed similarly to that in the open cuttings—the bottom and sides being lined with puddle 2 feet thick, carried up to 6 inches above the water-level. The puddle was made with clay, spread in courses 8 inches thick, twice cut, and well trodden. On the puddle at the bottom, a layer of furnace cinders, 6 inches thick, was spread. The towing-path walls, 22½ inches thick, were protected by cast-iron guards weighing 141 lbs. to the yard. Each guard was tied to the wall of the tunnel by a 1⅛-inch rod fastened to a cast-iron plate in the wall. The towing-paths were covered with a layer of red ashes 6 inches deep.

The total cost of the tunnel was 155,000*l.*—say, 50*l.* per lineal yard—which includes the cost of the shafts and the tunnel-faces. The cost of the tunnel alone was 39*l.* 5*s.* per lineal yard; and with canal and side-walls, it was 45*l.* 5*s.* per yard.

CHAPTER XX.

ENLARGEMENT OF RAILWAY TUNNELS.

THE operations for enlarging a railway tunnel, constructed originally for a single line of rails, so as to receive a second line of rails, are of great practical interest, by reason of the peculiar difficulties arising from the disturbance of soils which had already been disturbed and more or less displaced before. Such operations are not common. In the first of the following instances, the enlargement was made entirely on one side of the original tunnel; in the second instance—that of the Lindal Tunnel—the original tunnel stood exactly in the middle of the position occupied by the larger tunnel.

ENLARGEMENT OF THE STAPLETON TUNNEL.

The Stapleton Tunnel is on the Bristol and Gloucester Railway, about three miles from Bristol. It was executed by Mr. C. B. Lane, in 1843 and 1844, as Resident Engineer for Mr. Brunel. It was carried through the shales of the coal-measures, locally called ‘duns,’ and was constructed for a double broad-gauge line, on the site of an old tunnel, which was about 9 feet wide and 12 feet high, through which the traffic on the Coal-Pit Heath Railway, leading from Bristol to Westerleigh, was originally carried. The section of the new tunnel, with the position of the old tunnel, in dot-lining, is shown in Plate XVII. The ground was in a very shaky condition, partly from the fact of the old tunnel having been before carried through the same place, and partly from some old coal-workings. The work was commenced in 1843, during a dry summer; and as there was no appearance at first of the pressure that afterwards exhibited itself, the archwork was carried on with but four rings

of brickwork in mortar. When the autumnal rains set in, the ground began to press heavily, so much so that the whole line of the tunnel could be traced along the surface of the ground by depression; and it pressed all the more heavily from the comparative shallowness of the ground overhead, of which the greatest depth over the arch was not more than 40 feet. On November 10, 1843, a length of the tunnel fell in, and it was found necessary to proceed with the centering as rapidly as possible, to prevent the whole of the work, so far as then constructed, from falling. Before the tunnel was completed, upwards of 200 lineal yards, or two-fifths of the whole length, had to be taken out and rebuilt. After the accident, the thickness of the brickwork was increased to five and six rings, laid in Roman cement. During the progress of the work, a little embarrassment was caused by the necessity of keeping the small tunnel open for traffic. Mr. Lane at first used framed centres, like those employed in the Buckhorn Weston Tunnel; but he found it very inconvenient, and subsequently he employed the skeleton ribs, shown in the figure.

The total length of the Stapleton Tunnel is 514 yards, or about three-tenths of a mile. It is 26 feet wide at the level of the rails, 28 feet wide at the springing, and 24 feet high. The side walls were built of sound-fitted rubble-work of Pennant sandstone; and the arch, of brickwork, was laid in blue-lias mortar, up to the time of the accident, after which Roman cement chiefly was used.

Statistical summary.—Total length of the tunnel, 514 yards. The work was executed in 130 lengths, the greatest length being 16 feet, and the least 6 feet; the average length was about 12 feet. An invert was put in wherever there was much lateral pressure.

Excavation.—The total quantity of excavation, with the labour expended on the excavation, and in putting in and taking out timbering, poling-boards, &c., were as follows:—

	Cubic yards.	Number of days of Miners and Labourers.	Cubic yards per man per day.
1. Green duns	19,698	10,280	1·92
2. Red duns	12,492	6,365	1·96
3. Coal, shale, &c.	1,400	460	3·04
4. Clay	1,072	412	2·60
Total	34,662	17,517	1·97

showing an average of 1·97, say 2 cubic yards, per man per day.

For one length, commenced October 2, and finished October 13, 1843, the following were the numbers of days of each class of labour on the work of excavation and timbering:—

Ganger	18 days.
Miners	83 „
Labourers	38 „

This may be taken as a fair average for the whole tunnel.

Timbering.—The total quantity of oak bars and props broken or otherwise destroyed in timbering the excavations was 6,715 feet, or 13 feet per lineal yard of tunnel.

The quantity of poling-boards unavoidably left in amounted to 25,710 square feet, or 50 square feet per lineal yard of tunnel.

The greatest number of bars used in one length was thirty-four, and the greatest number broken in one length twenty-three. From eight lengths only was all the timber saved and taken out.

Masonry in side walls.—The side walls of a 12-feet length contained 32 cubic yards; for which the labour was—

Masons	12 days.
Labourers	12 „

being 2⅔ cubic yards per day.

Brickwork in mortar.—The arch of the tunnel, of four rings thick, contained 28 cubic yards in a length of 12 feet. Where no difficulty was experienced in removing the timber, the labour stood as follows:—

Bricklayers	12 days.
Labourers	15 „

That is to say, 1 bricklayer and $1\frac{1}{4}$ labourer executed $2\frac{1}{3}$ cubic yards per day.

The average of several lengths gave, for this quantity of labour, 2 cubic yards per day.

Brickwork in cement.—In building several lengths of brickwork in cement, five rings thick, every course gauged on the bed to the radius of the centering, and the three rings next the soffit worked alternately header and stretcher, the following were the averages of labour for one 12-feet length, containing $36\frac{1}{2}$ cubic yards:—

Bricklayer	20 days.
Labourer	30 „

or 1 bricklayer and $1\frac{1}{2}$ labourer to 1·8 cubic yards of work per day, including the gauging of the cement.

Centre-setting.—Two experienced foremen and six labourers set four ribs in one length, including propping and putting in sills, in one day.

Crushed work.—The labour on taking out and rebuilding a 6-feet length of crushed or broken work was—

Miners	12 days.
Labourers	10 „

In lagging up centres under a broken 12-feet, the time was—

Carpenters	4 days.
Miners	4 „

Masonwork of the arch.—The dimensions and quantities of the work of the arch, when completed, were as follow:—

	Lineal yards.
Brickwork in cement—6 rings thick	122
5 „	280
Brickwork in mortar—6 „	10
5 „	48
4 „	47
Coursed rubble in mortar, 2 feet thick	7
	514
Total length taken out and rebuilt in cement	219

Roman cement.—$36\frac{1}{2}$ cubic yards of brickwork required, on an average, 5 tons 4 cwt. of cement, gauged with sharp furnace-ashes in the proportion of 2 cement to 1 ashes; being, including all waste, about 2·9 cwt. per cubic yard.

Contract prices.—Ordinary excavation in the tunnel, 3*s.* 6*d.* per cubic yard; for rock, 7*s.* per cubic yard.

Brickwork in mortar, 25*s.* per cubic yard; in cement, 30*s.* per cubic yard.

Rubble-masonry in mortar, 15*s.* per cubic yard; and for ashlar, 2*s.* per cubic foot, or 54*s.* per cubic yard.

Prices paid for sub-contract work.—Excavating the first length at each end of tunnel, 6*l.* per lineal yard; excavating other lengths, from 5*l.* to 6*l.* per lineal yard.

Masons, 3*s.* per cubic yard.

Brickwork in mortar, 4*s.* 6*d.* per cubic yard; in Roman cement, 6*s.*

Centre-setting, including setting profiles, 10*s.* per rib.

Mining of broken work, 2*l.* per lineal yard.

Mortar rubble-packing behind arch, 2*s.* per cubic yard.

Cost of materials.—Pennant sandstone, beds and joints rough-dressed, for side walls, from 4*s.* to 4*s.* 6*d.* per square yard.

Bristol bricks, delivered at the tunnel, 29*s.* per thousand.

Keynsham lime (blue lias), 2*s.* 8*d.* per quarter of eight bushels.

Roman cement (Harrison's, of Pontypool), delivered at Bristol, 2*l.* 6*s.* per ton of six casks.

Oak bars, 8*d.* per lineal foot.

Poling-boards, elm, 16*s.* per 100 square feet.

ENLARGEMENT OF THE LINDAL TUNNEL, ON THE FURNESS RAILWAY.

The first contract entered into, was made for a tunnel, with a double line of way, with Messrs. Fell & Jopling, in June 1847; but it was annulled, after the works had been in progress for five months, in consequence of the monetary crisis of that period. If the contract had been completed, the tunnel would have cost—

	£	s.	d.
In rock, per lineal yard	21	0	6
In masonry, per lineal yard	45	0	0

After a suspension of about a year, a fresh contract was entered into for a tunnel of a single line, which was executed, completed, and opened in June 1851. The tunnel was about three-eighths of a mile in length, and it passed through material consisting of limestone rock, pinule, loose gravel, and clay with loose boulders; and the foundations throughout were good. When lined, it was 14 feet 6 inches high, and 12 feet wide; and it cost as follows:—

	£	s.	d.
In rock, per lineal yard	6	0	0
In masonry, per lineal yard	15	10	0

In consequence of the increase of traffic, it was decided, in 1854, either to enlarge or open-cut the tunnel. The plan of open-cutting was entertained, in case it might be necessary to ensure the regular working of the traffic during the progress of the works; but the additional cost of open-cutting over that of simply enlarging the tunnel was estimated at 12,000*l.*, and from the tenders received it appeared that it would have cost more than twice as much. It was determined to enlarge the tunnel, and the tender of Mr. William Tredwell was accepted. The contractors who tendered generally preferred or proposed to construct a supplemental tunnel rather than be subjected to the interruptions that must of necessity be caused by the trains during the operation. Mr. Tredwell offered to construct another single tunnel, with the necessary additional excavation, for the same sum; but this proposition was not favourably entertained. There was no precedent for a work of this kind; and there were disadvantages, besides, in working single tunnels—the difficulty of properly lifting and packing the permanent way by reason of the stifling atmosphere that is raised after the passage of heavy trains, which prevents platelayers from working for any great length of time together; and the condensation of steam upon the rails—all of which increases the expense of working. Besides, the tunnel was on a gradient of 1 in 100.

It will be seen from the illustration (Plate XVII.) that the tunnel was to be increased in width equally on each side, the level of the rails remaining the same. It was proposed that there should be two shafts, one on each side of the existing tunnel, so that the mining operations could be proceeded with, and the materials be removed, without interfering with the shell of the small tunnel. This, it was intended, should act as a protection to passing trains until some lengths of the large tunnel had been completed. In consequence of these conditions, the section of the proposed tunnel was considerably in excess of what has usually been allowed for two lines of railway.

The works for the enlargement of the tunnel were commenced in June 1855, at the old shaft No. 3, which was widened, instead of two new shafts being sunk, as at first contemplated. The line was given up to the contractor for eight hours a day, during the night. The shaft was divided down the centre by a strong timber brattice, so that it could be worked as two separate shafts. Top headings were driven, for short distances, at the proper levels, above the existing tunnel. The material was found to consist of dry, hard clay and gravel; but it was observed, both in widening the shaft and in driving the headings, that the ground had become set and broken up, from mining operations, to a much greater extent than could have been anticipated. As it was probable that such might be the case, more or less, throughout, and as it would, when wet, render the ground very treacherous, it was thought advisable to make the tunnel for the double line of less dimensions than at first intended. The crown was kept sufficiently high to allow the mining operations, in getting out the roof, to proceed, without interfering with the original tunnel. Wrought-iron centering was employed where necessary; also a shield to support the masonry of the small tunnel whilst a length was being excavated above, which served, besides, as a protection to the railway. The roof of the first length was executed by placing the sills for the support of the bars three feet above the crown of the small tunnel, on which and on the material forming the sides of the tunnel, they rested. A portion of the masonry of the small tunnel was then removed, and the excavation for the side walls was proceeded with. Working by shafts was afterwards dispensed with, as the alteration in the size of the tunnel did not permit of the excava-

tion for the side walls being taken out before the masonry of the smaller tunnel was removed.

In order to obtain another face to work at, it was necessary to break through the original tunnel, which, in fact, was used as a bottom heading. The operation was commenced by drilling through the soffit of the arch, to ascertain the nature of the material above. If satisfactory, a manhole was made, and the earth was removed, by means of a bar, until the excavation was sufficiently large to admit a miner. The hole was then timbered all round, leaving the top open. Another length of a few feet upwards was excavated, and timbered in a similar way; the process being repeated until the level of the top heading was reached. From this upright shaft the headings were driven, and the ordinary method of tunnelling was adopted. After a few lengths were completed, a regular system of timbering and of working was instituted, little distinction being made between light and heavy lengths. The bars used were chiefly of larch, varying in size from 15 to 18 and 22 inches in diameter; they were placed from 12 to 15 and 18 inches apart round the roof, and supported at each end by props from the sills, which were of pitchpine, from 20 to 22 inches square. A saddle, or half-balk, was placed on the top of the sills, and fastened to them with wrought-iron glands. The sills were supported from the ground by two upright props passed through the haunches of the small arch down to the formation-level of the tunnel, by which means only a small portion of the weight of the roof was thrown upon the small tunnel. After the excavation of the upper portion down to the level of the sills had been completed, the arch of the old tunnel was taken down, the side walls removed, and the excavation at the sides proceeded with. A portion of the small tunnel, from two to three feet in length, was always left in front of the sill, to prevent any materials falling on the railway. The sill was then further stayed by raking-struts from the formation-level. Small sills were placed about halfway down the side walls, to carry the props supporting the ends of the first sill, and these again were propped up from the foundations as the material was removed. A second or back upper sill was sometimes placed, to assist in carrying the crown bars; it was either propped from the bottom or from the smaller sills at the sides.

A framing, called by miners a 'horse-head,' was also frequently used. It consisted of two balks, or bars, placed upright, with a cross piece or cap at the top, of sufficient length to take the drawing bars, usually seven in number. This, when well packed up to the bars, greatly relieved the sills. When the ground was more than ordinarily heavy, the lengths of excavation were reduced from 15 feet to 12 feet, 9 feet, or even 7 feet. In some instances it was necessary, after the roof had been timbered, to put in additional bars, called lining bars, with those already placed. These were propped from the sill, or were carried by horse-heads. When well packed with other timbers, they formed a nearly solid timber roofing, 14 to 18 inches thick, for 12 or 14 feet round, exclusive of the poling-boards between the material excavated and the bars.

Four years had elapsed between the completion of the small tunnel and the commencement of the enlargement. This was considered sufficient time for all settlements and runs, from previous mining operations, to have become consolidated. But the displacement of the roof had been very great, and, from the nature of the material, the water appeared to have been impounded in the settlements, forming small reservoirs. One of these was met with near shaft No. 4, the two faces then being 90 feet apart. In one heading, the materials, which were very wet, consisted of clay, gravel, and large stones, and soon became converted into mud, which oozed through the timbers, filling up the heading and displacing the framing. After a large quantity of mud had been removed, the run subsided, and the excavation became more consolidated; then a continuous dropping was heard in advance of the work, giving signs of a cavity, whence, no doubt, the mud had issued. On widening out the boundary, a large hole was discovered, the top of which was 70 feet above the rails and 28 feet below the natural surface of the ground. It was supposed that the cavity was a natural reservoir, supplying distant springs, and that a vein of clear gravel and sand, which was cut through, had acted as a conduit. The mouth of the hole was timbered, and, as far as possible, the entire place was filled up. The vein of gravel, from the first, showed symptoms of running; and when the length was widened out, cutting the vein across its full extent, the length fell in, causing a

cessation of the traffic. The works were soon reinstated, fresh lengths were put in, and the work was completed beyond the shaft and the cavity without further accident.

The masonry, both for the side walls and for the arch, was of fitted limestone rubble, from 2 to 3 feet in thickness, set in Abershaw lime-mortar. The stone was obtained from the adjoining cuttings. A length of tunnel of 15 feet was excavated, on the average, by eighteen working sets or shifts of eight hours, representing one day's work of 60 miners and 75 labourers, but some lengths occupied as much as thirty-three working sets, or one day's work of 103 miners and 120 labourers. Of this number, eight sets were generally occupied in getting in the crown bars. The amount of excavation in each length was about 300 cubic yards.

The time occupied in building the side walls of a length of 15 feet averaged two sets, and in building and keying the arch, eight sets; employing in all 32 masons and 40 labourers, one day each. The time of the masons and labourers was scarcely found to vary; any additional time was easily accounted for by the difficulty in setting the masonry amongst the extra timbering used in heavy lengths. The ribs or centres were set by a leading miner and some labourers; it occupied about two sets, employing two miners and ten labourers one day.

The whole of the work was completed in about seventeen months, from June 1855 to November 1856. The number of trains that passed through the tunnel averaged eighteen trains per day. The length of the complete tunnel was—

In solid limestone rock	123 yards.
In loose material, lined with limestone rubble masonry .	337 „
Total length	460 „

The portion of the tunnel executed in masonry was completed in sixteen months. For the first eight months, four faces only were in progress, when 87 lineal yards were completed, being at the rate of 2½ yards per week, or less than 2 feet per week at each face. The actual time expended in completing each length of 15 feet averaged thirty sets or days. If calculated

according to the total time that the works were in course of construction, it would therefore appear that as much time was necessary as an allowance for contingencies, as for the actual execution. Great difficulty was experienced in obtaining workmen and in keeping them regularly at work.

The total cost of the tunnel, when completed, was as follows :—

	£	s.	d.
In 1849, the contract price for the small tunnel, in rock, per lineal yard	6	0	0
In 1854, the additional cost, when enlarged	21	4	0
Total cost of the double tunnel, in rock, per lineal yard	27	4	0
In 1848, the contract price for the small tunnel, lined with sandstone rubble masonry, per lineal yard	15	10	0
In 1854, the additional cost of widening	38	0	0
Total cost of the double tunnel, lined with fitted limestone rubble masonry	53	10	0

The rate of 6*l.* per lineal yard, as the cost of the original small tunnel in rock, is equivalent to 6*s.* 2*d.* per cubic yard of solid rock—a fair price when the material is not excessively hard.

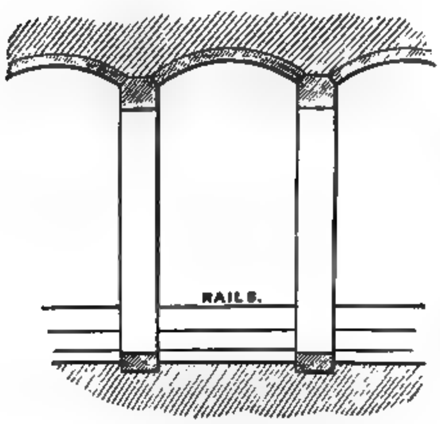
CHAPTER XXI.

OPEN TUNNELS.

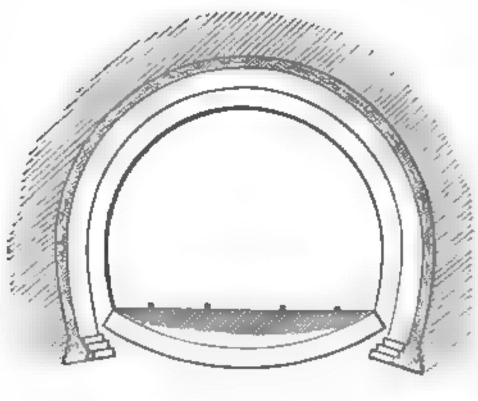
WHERE land is valuable, or where it is preferred to avoid the permanent severance of land, tunnels are substituted for shallow cuttings; and they are formed by open cuttings in the first place, building the tunnel in the cutting, and covering it in. The tunnels are said to be made in open cutting, and are known as *open tunnels*, or as *covered ways*. The sides of the cutting are made vertical, or nearly vertical, and they are supported by timber framing till the masonry of the tunnel is finished.

THE MOSELEY TUNNEL.

The first open tunnel constructed for a railway was probably the Moseley Tunnel, on the Birmingham and Gloucester Railway. It was constructed in a



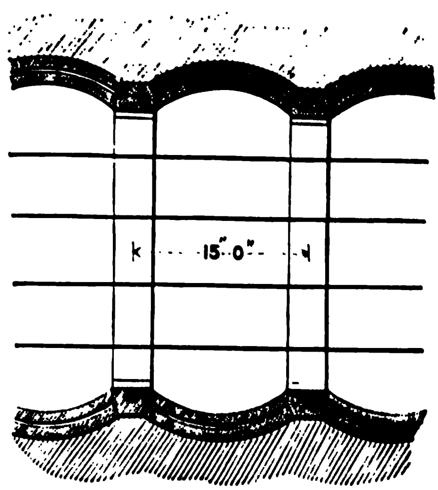
MOSELEY TUNNEL—LONGITUDINAL SECTION.



MOSELEY TUNNEL—TRANSVERSE SECTION.

cutting near the village of Moseley, the average depth of which was 30 feet, with firm gravel and dry sand at the top, which became wet below, and

terminated in a quicksand at the level of the rails. The authorities of Moseley had the power to require a certain portion of the line near the village to be in tunnel, about 200 yards in length, and it was considered to be the least expensive plan to make an open cutting in the first place, and afterwards to put in the brickwork of the tunnel. A series of inverts, 15 feet apart, were put in under the railway; and upon the ends of these hoops or buttress-rings were built, which spanned the tunnel. The intervals between the buttresses were filled by arched or concave walls. The whole construction, when completed, presented the segmental appearance of a caterpillar, and was called the 'caterpillar system.' (See the annexed illustration.) The inverts and buttress-rings were 27 inches square, and the concave walling and roofing were but 9 inches thick, backed with a little concrete. The work stood well.



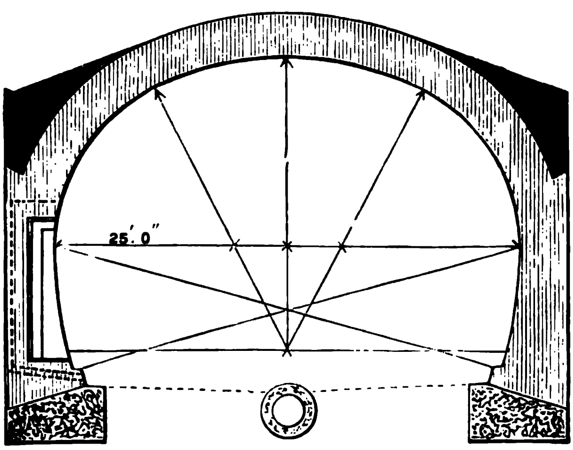
MOSELEY TUNNEL—PLAN.

THE METROPOLITAN DISTRICT RAILWAY (LONDON).

The whole of the tunnelling of the District Railway, of which Mr. Fowler is Engineer, was put in with open cutting. Two trenches were excavated at the proper distance apart to receive the side walls. The sides of the trenches were supported by struts and poling-boards, and the walls were built in to the level of the springing of the arch. As the construction of the walls proceeded, the timbering was removed and replaced by concrete backing behind the walls. The earth in the middle, called the 'dumpling,' or core, was excavated to such a level as to admit of the centering being put into position for the turning of the arch. When the arch was built and the centering removed, the dumpling was excavated down to the floor, from the ends, whence the stuff was conveyed away. By this economical method of procedure, the only

earth and gravel that was required to be lifted was that which was excavated in forming the trenches for the side walls; it was raised by means of steam cranes travelling on temporary rails laid by the side of the excavations. Again, the centering, which was supported on the core, was simpler and less costly than ordinary centering, as it rested on the ground, which was, besides, available as a roadway for the conveyance of material or the removal of the spoil. The facility for transport thus afforded, meantime, over the ground allotted to the tunnel, was an important matter, in the midst of crowded localities.

The normal or standard type of arched covered way, shown in the annexed figure, was only deviated from where a less depth than 19 feet was available, or where open cuttings with retaining walls were provided for ventilation. The arch has a span of 25 feet, and is 15 feet 9 inches above the level of the rails. The crown of the arch was struck with a radius of 15 feet 9 inches, the haunches with a radius of 9 feet 6 inches, and the side walls, with a curved batter on the face, to a radius of 25 feet.



THE DISTRICT RAILWAY (LONDON)—NORMAL TYPE OF ARCHED COVERED WAY OR TUNNEL.

The side walls are 27 inches thick at the springing, and the backing of the walls is carried down vertically to the foundation. The arch was ordinarily built of 5 rings of bricks; the number of rings was increased occasionally to 8, 9, or 10 rings. Bonding courses were introduced in the crown and the haunches. The haunches of the arch are backed with concrete, as shown, and the whole of the crown of the arch and the concrete is coated with asphalte $\frac{3}{4}$ inch thick in two layers. Behind the side walls, drain pipes were led down to a point near the footings, and then carried through the walls. Inverts were only placed where, from the nature of the soil, or from excessive lateral pressure, the floor was thought likely to rise. In the absence of an invert, the footings of the tunnel rest upon concrete foundations 30

CHAPTER XXII.

TUNNELLING IN HARD ROCK—TUNNELS ON THE AQUEDUCT OF THE GLASGOW WATERWORKS.

THE aqueduct of the Glasgow Waterworks, of which Mr. J. F. Bateman was Engineer, is 25¾ miles in length—that is to say, from Loch Katrine to Mugdock reservoir. Of this length, 13 miles consist of tunnelling, comprising eighty separate tunnels, for the construction of which forty-four shafts were sunk. The works were commenced in 1856, and the aqueduct was completed and opened in 1859.

For the first ten miles, the rock consists of mica-schist and clay-slate,—close, retentive material, into which no water percolates, and in which consequently few springs were to be found. 'This rock,' says Mr. Bateman, 'when quarried, was unfit for building purposes; there was no stone of a suitable description to be had, at any reasonable cost or distance, no lime for mortar, no clay for puddle, and no roads to convey material. Ordinary surface construction was, therefore, out of the question. . . . The aqueduct may be considered as one continuous tunnel. As long as the work continued in the primary geological measures, we had no water; and even after it entered the old red sandstone, and when it subsequently passed through trap-rock, there was much less than I expected.'

The tunnels were constructed with a flat floor, vertical sides, and a semicircular arch, 8 feet wide and 8 feet high at the centre, except in loose rock, which was not watertight, when the arch and the sides were formed slightly elliptical, to a width of 8 feet 6 inches, with an invert. The three types of section, according to which the tunnel was constructed, are shown in Plate XVII.; of which the first, simply excavation, is formed in solid watertight rock: the second, through watertight shale and soft rock, with 15-inch walls

in rubble and mortar, and 9-inch arch parpoints set in mortar, packed behind with dry rubble; the third, through soft rock or shale, not watertight, with 9-inch brickwork in mortar throughout, an extra half-brick thickness at the sides, and dry rubble packing above the arch.

The aqueduct begins with the first tunnel, which abuts on Loch Katrine, and is cut through the ridge which separates Loch Katrine from Loch Chon Valley, consisting of clay-slate and mica-schist, with beds of gneiss, mixed with quartz. The tunnel is 2,325 yards long, and is 500 feet below the level of the summit of the ridge. Twelve shafts were sunk from the surface, varying in depth from 14 yards to 163½ yards, making an aggregate length of 1,173 yards, or half the length of the tunnel. Their average distance apart was about 200 yards. The entrance to the tunnel is shown in elevation and longitudinal section in Plate XVII.

The next important tunnel is the Clashmore Tunnel, through a ridge of old red sandstone conglomerate, 1,175 yards in length; for the construction of which three shafts were sunk, respectively 53, 22½, and 29 yards deep.

The aqueduct terminated in the Mugdock Tunnel, 2,640 yards long, through a ridge of amygdaloidal trap, in which seven shafts were sunk, averaging about 130 yards apart.

Several portions of the tunnels were lined with brick. In some places the rock, which was at first considered durable, was found to perish after exposure to the atmosphere; the old red sandstone was, for this reason, lined to a considerable extent.

The rock was drilled for blasting by hand labour. It proved to be extremely hard and difficult to work, especially the mica-slate. In many cases, in cutting the tunnel through the rock, this progress did not exceed 3 lineal yards per month, at each face, though the work was carried on day and night. The average advance in the mica-slate was about 5 yards per month, or 7 inches per day. The bore-holes were 1¼ inch in diameter, and their ordinary depth was 20 inches. The drills required to be removed at every inch of depth, and the time occupied in drilling a hole was about an hour and three-quarters, equivalent to ⅕ inch per minute. A gang of

men working at an 8-feet face, started at night with a supply of sixty drills or jumpers, and brought out sixty dulled drills in the morning. As there were often 100 faces wrought at once, hand labour was considered preferable to perforating machines for the work. The junctions, upwards of 200 in number, were exact, and could only be traced by the crossing of the drill-holes blown out.

The ruling gradient, or fall, of the aqueduct is 10 inches per mile, equivalent to 1 in 6,336; and the aqueduct is capable of passing 50,000,000 gallons per day.

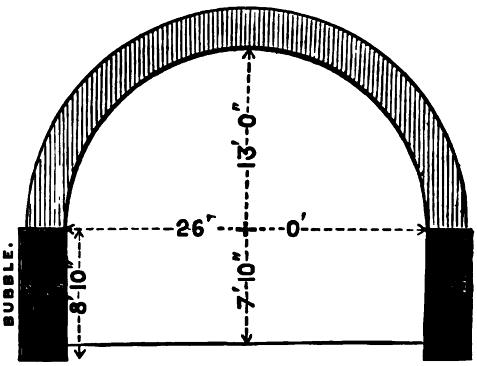
The actual cost of removing the rock by blasting varied from 1*l.* to 2*l.* per cubic yard. The cost of tunnelling through the mica-slate was about 13*l.* per lineal yard; and through the clay-slate from 9*l.* to 10*l.* per lineal yard. In the old red sandstone, where the discharged water was so considerable as to retard the progress, the cost in the lower beds of the stratum was about 10*l.* per lineal yard. Through the softer strata the cost of excavation was 8*l.* per lineal yard, and in some cases even less than that. These costs include the cost of the shafts, except where they were of considerable depth, as in the Loch Katrine Tunnel, for which the cost of the shafts is not included. The cost of driving through soft material, and of lining, taken together, was about equal to the cost of excavation through hard and compact rock, when no lining was required.

CLIFTON TUNNEL.

The Clifton Tunnel is situated on the Clifton Extension Railway, constructed by the Great Western and Midland Railway Companies. Mr. Brunlees was the Engineer-in-Chief, and Mr. J. G. Morrison the Resident Engineer, of the line. Mr. Lawrence was the contractor. The tunnel passes through mountain limestone, under the Durdham Downs. The work was commenced in the end of 1871, and completed in the beginning of 1874.

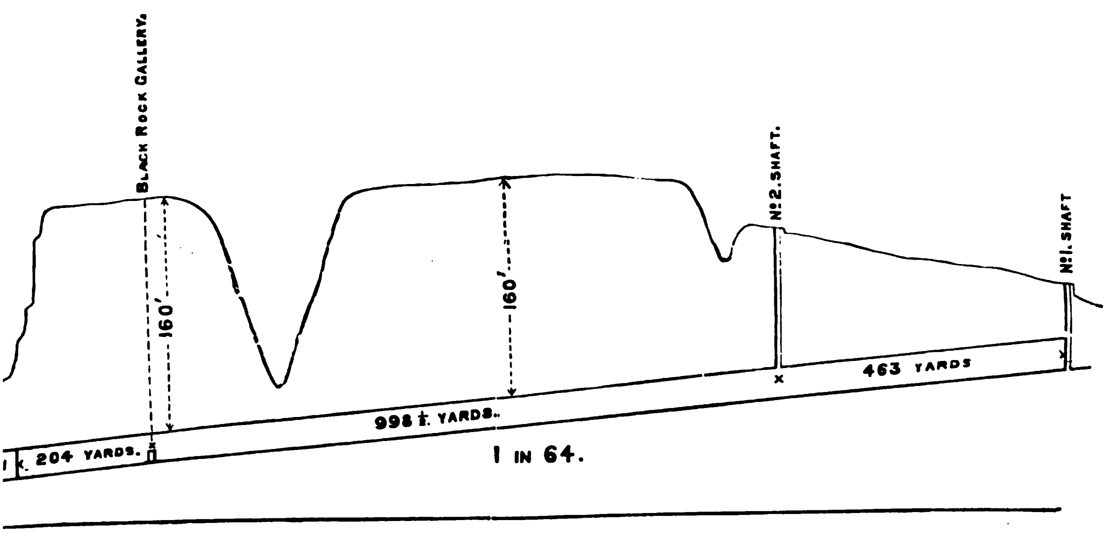
The tunnel was originally designed for two lines of way on the 7-feet gauge, with a width of 29 feet, and a height of 20 feet above the level of the rails, or 21 feet 10 inches above the formation-level, or the floor. After a few lengths had been made to these dimensions, near the side-drift and the shaft,

the width of the tunnel was reduced to 26 feet, for a double line of the ordinary gauge, and the height to 19 feet above the rails, or 20 feet 10 inches above the floor. (See the annexed figure.)



CLIFTON TUNNEL—NORMAL SECTION.

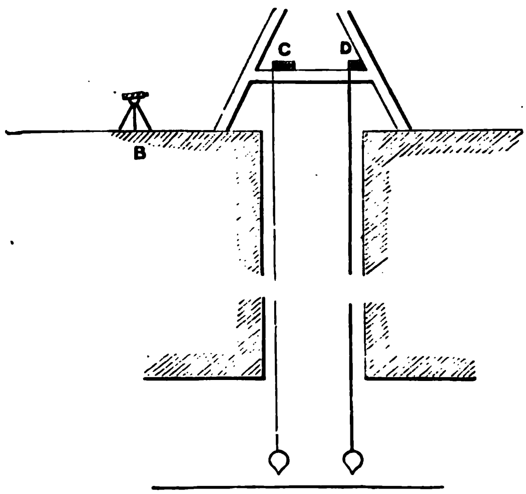
The tunnel is straight, on an incline of 1 in 64. It is 1,737½ yards in length. At a distance of 276 yards from the lower end of the tunnel, where it approaches to within 140 feet from the face of the Blackrock Cliff, a gallery or side-drift, 9 feet square, was opened from the face to the line of the tunnel. At a further distance of 998½ yards, a shaft (No. 2) was sunk, 102½ feet deep to the crown of the tunnel; and 463 yards further on—being at the upper end of the tunnel—another shaft (No. 1) was sunk, 30 feet deep. From these



CLIFTON TUNNEL—LONGITUDINAL SECTION.

three points—the side-drift and the two shafts—the tunnel was driven, the two extreme lengths by hand labour, and the intermediate length, of nearly 1,000 yards, with the aid of diamond boring machines. (See the section annexed.)

made. Plumb-bobs of 56 lbs. were let down the pit, the wires by which they were suspended being allowed to slide over the edges of the planks. In this way the wires were straightened; and when the bobs arrived within a foot from the floor of the tunnel, the wires were made fast. The instrument was again pointed at the pole A, which could be seen distinctly, though the wires intervened, as these were out of focus. Then it was focussed on each wire successively, when the wire was set exactly in line with the point of a knife. In focussing the instrument on the further wire, the nearer wire was gently held a little to one side, that the further wire might be seen.



The wires, which were nearly 100 inches apart, having thus been got into line, each plumb-bob was immersed in a bucket of water to steady it, and in the course of half an hour the bobs became perfectly still. Four points in the roof of the heading were then given independently of each other, by making an observation from behind the wires, when they ranged in line. The points were fixed successively by means of a small plumb-line hung from pieces of wood temporarily fixed to the roof. Lights were placed at all the four points, and at the wires, and when they were observed from one end, with the aid of a plumb-line, they were found to range exactly in line. Holes were then made in the roof near these points, into which wooden plugs were driven, and staples and rings were fixed in line by looking along and putting them in line with two other points. By these means, it was believed, the line was given below without any error exceeding half an inch per 100 feet. The extreme points given were 220 feet apart.

In verification of the substantial accuracy of the alignments, it may be stated that when the top heading from the lower end of the tunnel met the top heading from the Blackrock gallery, the junction was perfect as to lines

and levels. Again, the headings between Nos. 1 and 2 shafts accorded so closely that the widening out was executed according to the given alignments. But, in continuing the line from No. 2 shaft towards Blackrock gallery, by the aid of a sight from No. 1 shaft, it was found that the newer and more correct line thus obtained did not coincide with the line previously given. At a distance of 300 yards from shaft No. 2, the old line was found to be 6 inches wrong. The heading from the Blackrock gallery, about the same time, met a small air-shaft that had been sunk about 210 yards from the gallery. A sight was taken between the centre of this air-shaft and a point at the lower end of the tunnel, when it was found that the straight line between these two points passed within 3 inches of the centre marks all along that portion of the tunnel.

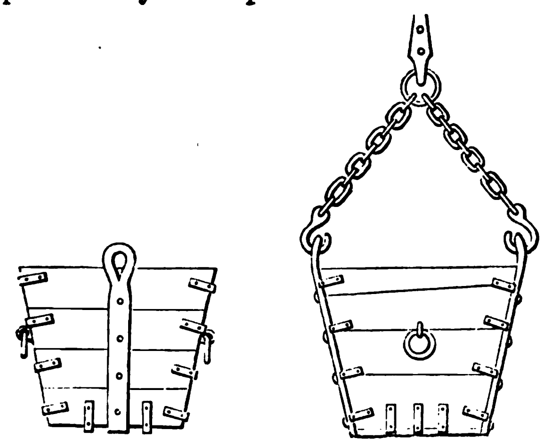
The rock excavated from the gallery or side-drift at Blackrock Cliff, as well as from the tunnel, was tipped from the end of the gallery into the quarry. The rock taken from the drift was a very hard dark-coloured limestone. The tunnel was reached after twelve weeks' work, night and day, showing an average rate of progress of nearly 11 feet per week, or, excluding Sunday, 21½ inches per day. The shortest distance driven in any week was 8 feet, and the longest 16 feet.

After some months of tipping, a bank was formed by the broken rock against the face of the cliff, upon which wooden sheds were erected.

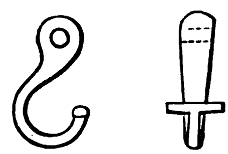
The rock was excavated in the tunnel, to the right and left of the gallery and also upwards to the crown of the tunnel, whence a top heading 8 feet square was driven into both faces. The tunnel was enlarged behind the heading, and attained to the full size of the excavation at a distance of from 20 to 30 yards from the face of the heading.

No. 2 shaft was rectangular in section, 9 feet by 10 feet across the tunnel. It was driven through hard limestone rock, in which there were numerous beds and fissures; and it was lined with timber for 85 feet of its depth, with settings from 3 feet to 6 feet apart, to prevent the falling of loose stones. The lower portion was solid, and did not require to be lined. The whole depth of the shaft, 102½ feet, was sunk in 56 working days of 24 hours, being at the average rate of 22 inches per day, the same rate at which the gallery

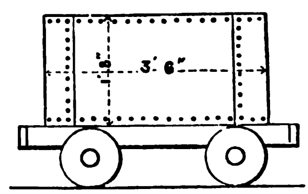
was driven. When the tunnel was reached, a top heading, 8 feet square, was driven each way, and enlarged to the full size of the excavation, as at the gallery, the shaft at the same time being carried down to the floor. The broken rock from the face of the heading was removed in wheelbarrows to the floor of the enlarged part of the tunnel, where it was filled into skips, which were run on trollies to the foot of the shaft, where they were raised by means of a jack-roll worked by two men, for the greater part of the time. A horse-gin was then substituted for the jack-roll, turned by two horses, and was used afterwards to raise the rock from the tunnel; it was finally superseded by steam-power.



SKIPS.



HOOK FOR SKIPS.



TROLLY.

The skips were of wood, 2 feet 6 inches square at the top, 2 feet square at the bottom, and 2 feet 4 inches deep, as in the annexed figures. To prevent the hooks from being accidentally disengaged, they were tipped with cross-heads, as shown by the figure. The gins were double-acting, so that as one skip was rising another was falling. When the rails were laid in the tunnel for the trollies, the exact positions for the loaded trollies at the shafts were marked, so as to bring the skip exactly under the rope, and to enable it to ascend straight. Before this was put in practice the horses, after having drawn up the skip a foot or two, were stopped until it was steadied. The saving of time by marking out the proper position of the trollies was considerable. One cubic yard of solid rock, when excavated, made five skip loads, and in each shift there were drawn about 100 skips of rock, and 20 skip loads of men and materials.

CLIFTON TUNNEL.

Table showing the advancement of the several Headings from time to time.

Number of working days.		Blackrock Gallery.			No. 2 Shaft.				No. 1 Shaft.	Lower end.	Total.
		Downhill.	Uphill.	Total.	Downhill.		Uphill.	Total.	Downhill.	By hand.	
		By hand.	By hand.		By machines.	By hand.	By hand.		By hand.		
Days.	Ending	Feet.	Feet.	Feet.	Feet.	Feet.	Feet.	Feet.	Feet.	Feet.	Feet.
	1871										
7	November 14	9	9	18	—	—	—	—	—	—	18
23	"	—	—	—	—	38	36	74	—	—	74
16	"	—	—	—	—	—	—	—	4	—	4
22	December 11	17	21	38	—	34	27	61	47	—	146
	1872.										
30	January 29	49	81	130	—	75	67	142	104	—	376
30	March 4	39	44	83	—	39	53	92	74	—	249
22	March 30	29	30	59	—	33	49	82	52	—	193
30	May 4	32	46	78	15	12	30	57	89	—	224
27	June 8	49	52	101	149	—	97	246	83	—	430
24	July 6	42	50	92	64	—	47	111	51	81	335
24	August 3	31	30	61	109	—	49	158	26	66	311
18	August 3	—	—	—	—	—	—	—	26	—	26
46	September 26	102	96	198	66	44	95	205	—	93	496
?	December 31	81	135	216	—	139	163	302	—	104	622
?	December 31	(Junction)	—	—	—	—	—	—	28	(Junction)	28
	1873.										
?	February 8	—	58	58	—	85	57	142	36	—	236
24	March 8	—	60	60	—	45	(Junction)	45	(Junction)	—	95
24	April 5	—	35	35	—	9	—	9	—	—	44
24	May 3	—	70	70	—	58	—	58	—	—	128
53	July 4	—	114	114	—	126	—	126	—	—	240
24	August 2	—	70	70	—	71	—	71	—	—	141
28	September 3	—	87	87	—	63	—	63	—	—	150
	1874.										
105	January 3	—	306	306	—	226	—	226	—	—	532
		480	1,384	1,864	403	1,097	770	2,270	620	344	5,098 or $1.699\frac{1}{3}$ yards.

When 52 yards of the heading had been driven, a hole was made in the roof, a break-up was made, and a top heading, 7 feet square, was driven both ways. In the top heading, driven towards the surface, two short shafts, about 50 feet apart, were sunk to the bottom heading, through which the excavated material was dropped into waggons below.

Excavation of the tunnel.—Though the top headings were commenced at a width and depth of 8 feet each way, they were excavated to widths of 10 and 11 feet as the work advanced; and finally to the full width of the tunnel, about 30 yards behind the face. The advancement of the headings severally, from time to time, is given in the preceding table. The work of

the headings was commenced at the Blackrock gallery on November 7, 1871, and two or three weeks later at the shafts. To January 3, 1874, embracing a period of about 25½ months, say 660 working days, a total length of heading of 1,699⅓ yards had been excavated, being at the rate of 2·575 yards per working day.

All the headings and enlargements were excavated by hand labour, with the exception of the lower heading at No. 2 shaft, a portion of which was bored by means of Captain Beaumont's diamond rock-drill. The diamond drill was kept at work for upwards of four months, and the heading was advanced 134 yards; after which the machine was withdrawn.

Labour.—In the work of excavation there were two shifts per day, of ten working hours each, making twenty working hours per day. In driving the gallery and sinking the two shafts, six or eight men and a ganger were employed at each point; that is, three or four sets of two men each, one to hold the jumper and the other to strike. As before stated, the average rates of progress were:—

	Per day of 20 hours.
For the Gallery	1·8 feet.
No. 2 Shaft	1·83 „
No. 1 Shaft	3·33 „

From the table it appears that the following were the mean rates of advance in the headings during the second quarter of 1872, when the work proceeded regularly:—

	Per working day of 20 hours.
Gallery, downhill heading, hand labour	1·52 feet.
Do., uphill heading „	1·83 „
No. 2 Shaft, downhill heading (in first quarter of 1875), hand labour	1·61 „
Do., do., machine labour	5·06 „
Do., uphill heading, hand labour	2·15 „
No. 1 Shaft, downhill heading, hand labour	2·75 „

The numbers of miners by hand labour employed during a portion of that period were as follows:—

	Miners.		Miners.	Total Miners.
Gallery, downhill heading	4	Enlarging	8	12
Do., uphill heading	4	„	20	24
No. 2 Shaft, downhill heading	6	„	20	26
Do., uphill heading	6	„	17	23
No. 1 Shaft, downhill heading	6			

It appears that, by means of the diamond-drill, the rate of progress w 3½ times that effected by hand-labour. The drill was worked by compres air, and it required the attendance of two men at the air-compressing eng and seven men at the machine itself. The cost of excavation by the diamon drill, including all proper charges, was greater than the cost by hand-labo

The holes which were bored in the front of the heading were twen four in number, from 3 feet to 3½ feet deep, of which the central ho converged inwardly, so that when they were blasted, a conical cavity w formed in the face. The blasting of the remainder of the face could th be effected with facility.

From observations that were made, it was found that, for the blast of 1 cubic yard of rock, two pounds of gunpowder, or the same weight dynamite, was consumed.

The rock was excavated, during the same period, at the following ra per day:—

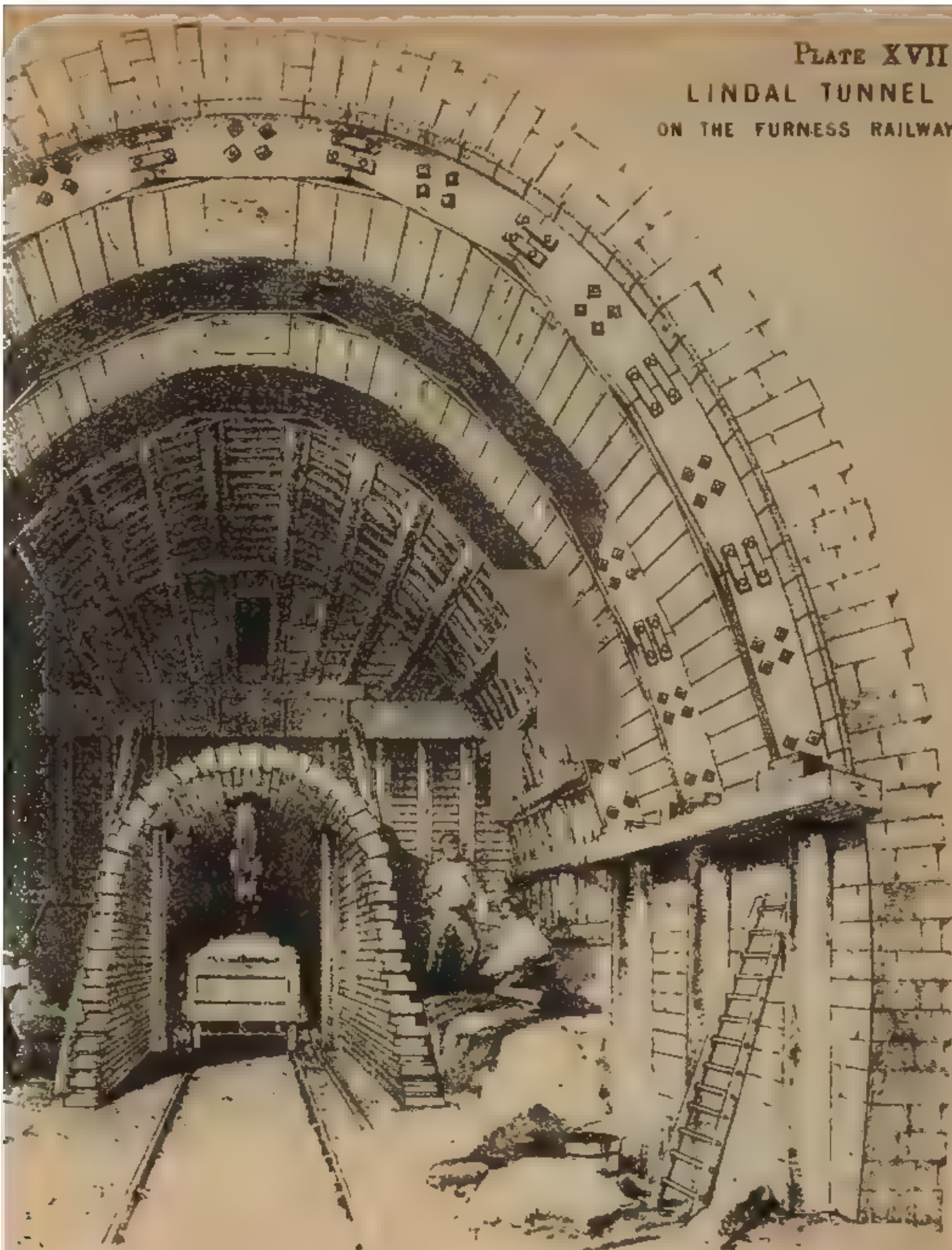
	Cubic yards.	Cubic yards.
Gallery—Two headings	7·8	
Enlargement	49·7	
		57·5
No. 2 Shaft—Two headings	13·8	
Enlargement	66·0	
		79·8
No. 1 Shaft—Two headings	6·4	
Enlargement	41·8	
		48·2
Total per day		185·5

Brickwork and masonry.—The arch of the tunnel was semicircular, a consisted of five rings of brickwork where the rock was very solid, and rings at other places. The walls were vertical, of stone 2 feet 6 inches th The tunnel was only partially lined, where lining was necessary.

PLATE XVII

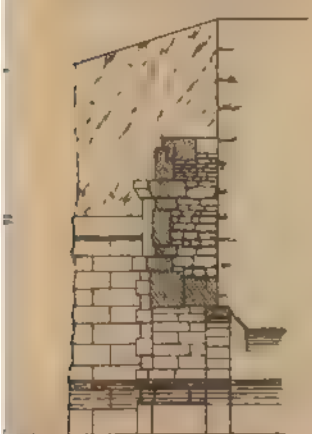
LINDAL TUNNEL

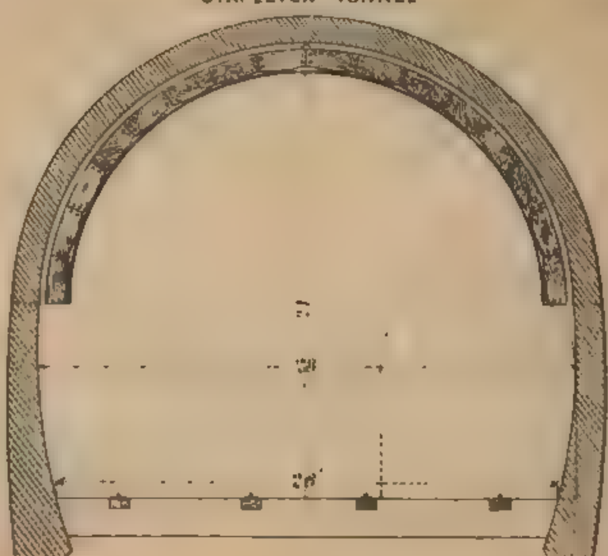
ON THE FURNESS RAILWAY



STAPLETON TUNNEL

SECTION OF ENTRANCE TO TUNNEL





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CHAPTER XXIII.

TUNNELLING IN HARD ROCK—MONT CENIS TUNNEL.

THE Mont Cenis Tunnel, through the Alps, is the completing link of the Victor Emmanuel Railway, which places France in direct communication with Italy. It passes from a point near Modane, in France, under the Col de Fréjus, about 18 miles west of the actual Mont Cenis, into Italian territory, at a point near Bardonnèche, about 24 miles from Susa. The principal levels are as follows:—

	Feet above the level of the sea.
Modane, or north entrance	3,801
Bardonnèche, or south entrance	4,236
Difference of levels of the two entrances	435
Summit of tunnel	4,246
Summit of section	9,527
Depth of summit of tunnel below summit of section	5,281 feet.

The length of the tunnel between the extremities is 12,233·55 metres (7·6016 miles). It is formed with a rising gradient from each end, at the rate of about 1 in 45½ from Modane, and 1 in 2,000 from Bardonnèche, the summit or meeting of the gradients being half-way through the tunnel.

The railway does not enter at the extremities of the tunnel, but joins it by means of special curved sections of tunnel at each end. At the north end, the curve is 496 yards long, on a rising gradient of 1 in 43½, and joins the tunnel at a point 378 yards from the extremity. At the south end, the curve is 827¾ yards long, on a rising gradient of 1 in 33, and joins the tunnel at a point 274¾ yards from the extremity.

The total length of tunnel traversed by the trains is, therefore, 12,846·92 metres (7·9806 miles).

The following is the geological formation of the rock traversed by the direct tunnel, advancing from the north end:—

	Metres.		Miles.
Carbonaceous schist	2,096·50	or	1·3027
Quartz	388·50	„	·2414
Limestone and dolomitic limestone . .	355·60	„	·2210
Calcareous schist	9,392·95	„	5·8365
	12,233·55	or	7·6016

The tunnel, on leaving Modane, is of the following dimensions:—25 feet 3½ inches wide at the base, 26 feet 2¾ inches wide at the broadest part, and 24 feet 7¼ inches high, the arch being nearly semicircular. At Bardonnèche the height is greater by 11¾ inches, and the arch is made elliptical, to enable it to resist the greater strain caused by a different inclination of the strata. The tunnel is lined, with the exception of about 300 yards on the north side. The side walls are stone, 8 feet 6 inches high throughout. The arch to the south side is constructed principally of brick, and to the north side of stone, a brick key being applied throughout. There are side paths of flagstones, 20 inches wide.

Through solid rock from end to end, the tunnel was excavated by boring and blasting with gunpowder.

The project of excavating the tunnel by machinery was put forward in 1857 by MM. Sommeiller, Grandis, and Grattoni, Engineers, who had already surveyed the line of railway, and who were even then engaged upon other works in which compressed air was employed. Whilst retaining the principle of excavation by boring and blasting with gunpowder, they proposed to use the pressure of compressed air to drive machinery for replacing the ordinary method of boring by hand-labour, and to employ water power for compressing the air necessary for the purpose. The project was accepted, and, pending the construction and erection of the machinery, a commencement was made at both ends, by ordinary hand-mining, in the year 1857. For three years, to the end of 1860, hand labour was employed for drilling the rock, at the south end, when it was replaced, in 1861, by machine-boring; but it was not until

after five years of hand-labour, at the end of 1862, that boring by machinery was introduced at the north end. A heading, or advanced gallery, about 10 feet square, was driven from each end, and subsequently widened out to the dimensions necessary for receiving the walls and arches. When machinery was introduced for driving this gallery, eleven perforating machines or air-drills were employed at the north end, and nine at the south end. But, in the middle of 1873, an experiment was made with a smaller gallery, 7 feet square, a size more in accordance with usual mining practice, and, if feasible, more economical to be worked out. Ultimately, a compromise was arrived at, and the advanced gallery was cut out permanently to a width of 9 feet 6 inches, and a height of 8 feet 6 inches, with seven perforators. It was enlarged at first by hand-labour, but this was found insufficient for the work of enlargement; for, although it was carried on at several points—as many as six points at each end—simultaneously, it was found impossible to carry away the rock extracted from the advanced gallery with so many blockages in the tunnel. At considerable increase of expense, so far as the actual enlargement was concerned, but with great gain in rapidity of advancement, the machine perforators were applied, in 1868, to that work, and the enlargement was concentrated to one point, at each end.

Gas, made at the surface, was used for lighting the tunnel at the south end, and was carried by pipes up to the forehead.

In Plate XVIII. are shown the form of the advanced gallery and the distribution of the perforations which were made in the forehead, according to the system of excavation first adopted. Three or four large holes, 4 inches in diameter, were bored about the middle of the forehead, the object of which, not being charged, was to ease the other holes and to increase the effects of the first explosion. These large holes were surrounded by the holes to be charged, which were 3 centimetres (about 1·2 inch) in diameter at the bottom. The holes in the forehead averaged eighty in number; and the space between the holes varied from 6 inches to 30 inches, according as the distance from the first breach was increased. All the holes were bored to a depth of from 32 to 39 inches (1 metre), and it was the intention that the rock should be blown out to the depth of the holes. The holes

immediately surrounding the large central holes were the first that were charged and fired; the rock was blown by the explosion into the large holes, and a considerable breach or cavity was formed in the middle, known to miners as a 'laying in.' The remaining holes in turn, by successive circuits, were charged and exploded, bursting inwards, towards the cavity, until the whole forehead of the gallery was blasted out.

The enlargement of the advanced gallery to the full size and form of the excavation for the tunnel was effected in four stages. The successive enlargements are shown in figs. 1 to 6, Plate XVIII.

Fig. 1. Advanced gallery, 9 feet 6 inches wide, 8 feet 6 inches high; driven by machinery, with seven perforators.

Fig. 2. First enlargement of the advanced gallery, to 12 feet square; by machinery, with five perforators.

Fig. 3. Second enlargement of the advanced gallery to 18 feet high; by machinery, with two perforators, the support (*affût*) being carried on rails resting on the timber framing in the gallery. A conduit is formed in the middle of the floor for drainage.

Fig. 4. Third enlargement of the advanced gallery, in the upper part, to the full size required, by manual labour.

Fig. 5. The upper part of the tunnel secured with arching.

Fig. 6. The lower part of the tunnel enlarged to the full size required.

Fig. 7. The tunnel completed. Arch, ·80 metre, or 31½ inches thick.

There was very little infiltration of water into the tunnel, and timbering was not required.

The masons obtained good foundations for the centres on the rock at each side, and the line of rails was kept clear for the transport of the broken rock, *déblai*, from the advanced gallery. In enlarging the lower part of the tunnel, a length of a few feet only was extended at a time, and supports or pillars of rock, 6 or 8 feet long, were left at intervals, with balks of timber laid from pillar to pillar to sustain the arch, until it was underpinned by the walls, which were built up as the rock was removed.

The advantage of the method of working by removing the side rock a little at a time consisted in preserving the surface to be finally exposed by

excavation from the action of the air, the walling being made as soon as possible after each length was excavated, in lengths of 6 metres, or about 20 feet each.

For removing the broken rock produced by blasting, there were two lines of rails at the north end, one on each side of the line, which carried the support and the perforating machines. The rock was removed in small waggons to the end of the advanced gallery, where it was tipped into larger waggons, and taken thence by horses outside the tunnel.

The rock was, in many places, of a quality exceedingly difficult to be worked—being soft in some places, and hard in others. The drills, constantly seeking the softer material, engaged themselves in the holes, and the extrication of them was a matter of difficulty and time. The rate of advance was, therefore, not so great in rock of such a nature as in that which was perfectly homogeneous. To bore holes 1 metre in depth and 4½ centimetres, or 1·8 inch, in diameter, in rock of unequal texture, occupied from twenty-five to thirty minutes, whilst in a hard but homogeneous rock, the boring of the hole could be performed in twenty minutes.

The drilling of the eighty holes in the forehead, in the earlier operations, had been done in five hours, in the softest rock; but when the rock was not homogeneous, or was excessively hard, it had taken from twelve to thirteen hours. In the end of 1863, the perforations were made in schist, and also in a soft and perfectly homogeneous material that had been taken for coal—a species of anthracite; and the progress for the last month was about 60 metres, averaging about 2 metres per day, at one forehead. In the beginning of the next year, a different material was struck, non-homogeneous, containing veins of quartz and hard stone; and the rate of advancement was reduced to half a metre a day. There followed, shortly, a seam of very hard but perfectly homogeneous rock, which was perforated more quickly—at the rate of about 1½ metre per day. These examples are quoted to show the beneficial influence of homogeneity in facilitating the operations of boring.

It was necessary, in making one hole, to use drills of four different diameters successively: namely, 4½ centimetres, 4 centimetres, 3½ centimetres, and 3 centimetres, owing to the reduction in the size of the cutting faces by

wear. In this way, the chamber was formed slightly conical, smaller at the base than at the entrance. The conical form, with the smaller end at the base, was unfavourable for blasting effect, since the line of greatest thickness and greatest resistance between the large and small holes, was at the base, and the explosive force of the powder very seldom destroyed the rock quite to the whole depth of the holes. The result of the blasting for making the first breach, could not be relied on; frequently, portions of the rock at the base of the holes were left, which had to be cut out with chisels before the subsequent discharges could be made. Though the holes might be made a metre in depth, the actual advancement for one shift was often not more than two-thirds or three-fourths of the depth. Again, in preparing for the first breach, it was very difficult to place a charge-hole equidistant from the two nearest large holes; hence, when the charge was fired, it blew the rock out into the hole where it found the least resistance, and left a column or piece of rock which, as above stated, had to be cut out, for it was an established fact that the extent of advancement depended upon the depth and size of the breach first made. In June 1863, at the south end, boring in calcareous schist, the average progress made was at the rate of ·845 metre, or 33·28 inches, for each shift. Under these circumstances, the operation of charging and firing the holes for one shift occupied from 1½ or 2 hours to 6 hours.

In the face of these imperfections of drilling, it was tried, with the earlier drills, to place the holes in rows so as to touch each other, and thus to form the first breach without the aid of blasting. But this plan was found to be impracticable, owing to the engagement of the drills in the holes, and the difficulty of extricating them.

To obviate the various objections to the old drill, a new drill for the large holes was employed, so far on the principle of the common pin-drill that it consisted of a guide-drill, which cut a 2-inch hole in advance, and a 6-inch drill, which followed it on the same shaft, and bored out the holes to 6 inches in diameter. The advanced drill was formed with checks by which it was steadied and held to its work of pioneering. The larger drill was composed of three cutting faces, and struck the rock twenty times in one revolution; and the cutting faces were so formed that the impressions made by them crossed

each other more than 4,000 times in each complete revolution, and the rock was quickly destroyed. With the old drill, the large 4-inch holes were drilled out at once to their full diameter, and in revolving they crossed the cuts in the centre only. One of the new drills made a 6-inch hole, 1 metre deep, in an hour; and the same drill had made three such holes in succession, equivalent to one 6-inch hole, 3 metres or 10 feet deep, without receiving injury. On the old system, as many as six drills were occasionally required to make one 4-inch hole 1 metre in depth.

The new drills for the charge-holes were made like the guide of the large drill. In turning, they struck towards the circumference of the hole; and a 1½-inch hole, 1 metre deep, could be bored in from ten to fifteen minutes, with one drill, about as wide at the base as at the entrance, and free from the taper of the holes produced by the old drills.

With the new system of drill, the first breach was formed without the aid of blasting, as a row of 6-inch holes could be bored, cutting into each other, and forming a continuous breach; whilst a 6-inch hole could be made in the same time as a 4-inch hole by the old drill.

According to the system of blasting, more lately approved, the cartridge employed was of a peculiar construction. It consisted of a cylinder of paper containing powder, fuse, and tamping; the tamping consisted of stone broken small, or of clean dry sand, and was rendered effective by enclosing in the cartridge, in front of or above the powder, a wooden wedge or cone, with the base towards the powder. Charging a hole consisted simply in placing one of these cartridges within it. The powder, in exploding, acted on the base of the cone, which, by its action, broke the paper enclosing the sand, and forced the sand against the sides of the hole. The cone, thus wedged in, presented a fixed surface, behind which the powder acted. The charge of powder varied from a third to a half the depth of the hole, depending on the nature of the material; but, with the perfectly secure conical tamping, a greater force was obtained from a given quantity of powder, and smaller charges were needed, than before it was introduced. Again, the holes bored by the new drills were practically cylindrical, and could be completely occupied by cylindrical cartridges driven to the bottom, and thus

the objection to the old conical hole was avoided—the difficulty of driving a cartridge to the bottom without leaving unoccupied vacancies. The charge of powder placed in a 1½-inch hole, 1 metre deep, was from 12 to 18 inches in depth, weighing from ¾ lb. to 1½ lb. It appeared that the average charge per hole was 1 lb. of powder; amounting to 80 lbs. for the 80 holes discharged for one shift.

The quantity of rock dislodged on the improved system amounted to about 14 cubic yards at one shift.

Another plan for making the first breach was tried. A conical hole was cut in the centre, of which the larger diameter was at the base, within the rock. By a simple contrivance, the drill was made to revolve at a slight angle with the centre line of the hole, like a conical pendulum, or an arm of an ordinary steam-engine governor—the centre of angular rotation, like the centre of suspension of the governor, being a fixed point in front of the rock, and the angular deviation being caused by the action of a strong spring, laterally on the spindle of the drill. Thus a hole could be made, 3 inches in diameter at the entrance, and 6 inches at the base. An unusually large quantity of powder could be placed at the base of the chamber, and, with careful tamping, the falling-in contour of the sides of the hole towards the entrance exposed the surface favourably for breaking up the rock, and the formation of a breach of considerable dimensions by a single discharge.

ADVANCED GALLERIES.

Progress of the gallery at the north end. Hand-labour.—From the end of 1857 to the end of 1862, about five years, the advanced gallery, or heading, was driven for a length of 921 metres, or 1007·3 yards, being at the rate of 1·65 feet per day. Twelve miners were constantly engaged in driving the advanced gallery; there were three sets, each working eight hours.

By machine.—From January 25, 1863, when the work by machinery was commenced, to June 30, 1863, 153 working days, the gallery was advanced 171·25 metres or 187·3 yards, being at the rate of 3·686 feet per day. The following is the performance month by month, and it is apparent

that, as the men acquired experience, the rate of advance was improved. The performance for the remaining six months of the year 1863 is added, for the sake of comparison :—

PROGRESS OF THE ADVANCED GALLERY BY MACHINE—NORTH END.

1863.	Working days.	Advance each month.				Advance per day.
January 31	6	4·43	metres, or	4·845	yards	2·42 feet.
February 28	28	23·31	"	25·493	"	2·73 "
March 31	31	34·44	"	37·667	"	3·64 "
April 30	30	31·42	"	34·367	"	3·44 "
May 31 .	31	38·80	"	42·433	"	4·11 "
June 30 .	27	38·85	"	42·489	"	4·72 "
Six months— December 31	184	204·75	"	223·873	"	3·65 "
Totals .	337	376·00	"	411·222	"	3·66 "

South end. Hand-labour.—From the end of 1857 to the end of 1860, when hand-labour was replaced by machinery, a period of about three years, the advanced gallery was driven 725 metres, or 793 yards, being at the rate of 2·148 feet per day. Twenty miners were constantly at work in driving the advanced gallery; and three sets or shifts per day of twenty-four hours.

By machine.—Little progress was made with the aid of machinery in the first year of its use, 1861, owing to the breakage of air-compressing machinery. The advance in 1861 was only 170 metres.

The greatest progress made in the galleries in any one month, was in May 1865, in the north end, when 121·80 metres, or 133·2 yards, was executed through carbonaceous schist, being at the rate of 12·90 feet per day.

The least progress, after the successful application of the boring machines, was in April 1866, also in the north end, when 10·67 metres, or 11·67 yards were made, through quartz, equivalent to 1·17 feet per day.

The total progress of the advanced galleries at each end, year by year, until a junction was effected, which took place on December 26, 1870, is shown in the following tables. The progress by hand labour is distinguished from the progress by machine. Columns are added to show the nature of the rock that was penetrated in each year.

MONT CENIS TUNNEL.

Yearly Progress of the Advanced Galleries.

Year.	North end (Modane).			South end (Bardonnèche).			Total.	
	Metres. By hand labour.	Yards.	Rocks.	Metres. By hand labour.	Yards.	Rocks.	Metres. By hand labour.	Yards.
1857	10·80	11·81	Carb. schist	27·28	29·83	Calc. schist.	38·08	41·64
1858	201·95	220·95	,,	257·57	281·68	,,	459·52	502·63
1859	132·75	145·17	,,	236·35	258·47	,,	369·10	403·64
1860	139·50	152·56	,,	203·80	222·88	,,	343·30	375·44
1861	193·00	211·07	,,	—	—	—	193·00	211·07
1862	243·00	265·75	,,	—	—	—	243·00	265·75
Totals .	921·00	1,007·23	—	725·00	792·87	—	1,646·00	1,800·10
	By machine.			By machine.			By machine.	
1861	—	—	—	170·00	185·91	Calc. schist.	170·00	185·91
1862	—	—	—	380·00	415·53	,,	380·00	415·53
1863	376·00	411·20	Carb. schist	426·00	465·87	,,	802·00	877·07
1864	466·65	510·34	,,	621·20	679·35	,,	1,087·85	1,189·69
1865	332·85	364·01	,,	—	—			
	125·55	137·30	Quartz.	—	—			
	458·40	501·31		765·30	836·94	,,	1,223·70	1,338·25
1866	212·29	232·17	,,	812·70	888·79	,,	10,24·99	1,120·96
1867	50·66	55·40	,,	—	—		—	
	355·60	388·89	Limestone	—	—		—	
	281·55	307·30	Calc. schist	—	—		—	
	687·81	752·19		824·30	901·47	,,	1,512·11	1,653·66
1868	681·55	745·35	,,	638·60	698·38	,,	1,320·15	1,443·73
1869	603·75	660·27	,,	827·70	905·18	,,	1,431·45	1,565·45
1870	745·85	815·68	,,	889·45	972·72	,,	1,635·30	1,788·40
Totals .	4,232·30	4,628·50	—	6,355·25	6,950·20	—	10,587·55	11,578·70
Total by hand labour and machinery	5,153·30 or 3·2021 miles.	5,635·73		7,080·25	7,743·07 or 4·3995 miles.		12,233·55	13,378·80 or 7·6016 miles.

On December 25, 1870, at 4.25 P.M., the machine perforator, No. 45, working on the Italian side, knocked a bore-hole, 12½ feet long and 2 inches in diameter, through the diaphragm of rock then separating the advanced galleries from Italy and France. A number of bore-holes having next been bored in the curtain of rock, they were fired on December 26, 1870, at 5.20 P.M., and the advanced galleries were thus brought into communication.

There was an error of only 1 foot in the calculations of the engineers as to the levels at the meeting of the two galleries, the north gallery being the higher. In the direction there was no error. The actual length of the tunnel proved to be 11½ metres more than was estimated. Some anxiety was, in consequence, felt in the last few days previous to the communication being effected, as it was feared that the ends had overlapped.

On the whole, better progress was made at the Italian than at the French end of the tunnel—partly owing to the softer and more favourable rock, and partly owing to the advanced gallery being carried forward on a smaller size on the Italian side. The different operations of boring, charging, firing, and removing the broken rock were, in the last two or three years, performed with much greater celerity than in previous years; and three complete shifts or repetitions of each operation were worked in the twenty-four hours. The advance made in 1870, the last year of operation, was more than double that of 1863, by machine; the advance of 1870 may be shown as follows, in contrast to that of the last years by hand labour:—

1862. Advance—North end	265·75 yards,	equivalent to	2·18	feet	per day.
1860. „ South end	222·88	„	„	1·83	„	„
Both ends, by hand labour	488·63	„	„	4·01	„	„
1870. Advance—North end	815·68	„	„	6·8	„	„
South end	972·72	„	„	8·1	„	„
Both ends, by machine	1,788·40	„	„	14·9	„	„

During the years here selected, the work was driven exclusively in schistose material, and may therefore be fairly compared. A mean advance of 7 feet per day at each gallery was made by machine, against a mean of 2 feet per day by hand labour, being in the ratio of 3½ to 1.

In the earlier stages of the work, strong doors were used, which were fixed at from 100 to 150 metres from the forehead of the gallery, and removed from time to time as the work was advanced. The perforating machines were removed behind the doors previously to discharging the holes bored. Subsequently, these doors were suppressed, and the saving of time was

considerable. The occasional damage done by loose pieces of rock to the machinery seems not to have been considerable.

The following particulars relating to the execution of 380 metres, driven in 1862, at Bardonnèche, were given before the Italian Parliament. 582 shifts were worked, of an average duration of 7h. 39m. for machines; and 6h. 2m. for exploding and removing broken rock. 18,622 kilogrammes (about 18·6 tons) of gunpowder were used; 47,751 holes were bored, from 30 to 32 inches deep, averaging 78·6 holes per shift; 76,000 metres (47 miles) of fuse were used.

The enlargement and the lining of the tunnel were kept up to within about 300 yards from the forehead of the heading in each direction.

Ventilation of the tunnel.—It was feared, and urged as an objection to the making of the tunnel, that the ventilation would, before it was finished, be so imperfect as to prevent, or at least materially to retard, its construction. It would have been almost impossible to employ any other motor than compressed air for working the machines in the forehead, since it affords, after its escape, a supply of fresh air to the workmen; and, by expanding from a greatly reduced bulk to its former volume, it materially reduces the temperature.

It was estimated that the supply of air necessary at each end for respiration, lighting, and blasting, would amount to about 128,000 cubic yards per twenty-four hours, at atmospheric pressure. As a matter of fact, nevertheless, it may be stated that in June 1863, when 1,092 metres (two-thirds of a mile) had been driven on the north side, and 1,450 metres (nine-tenths of a mile) on the south side, there were no means specially adopted for ventilation. The exhaustion from the perforators was adequate to the requirements of the men in the advanced gallery. Each machine used 8 cubic feet of compressed air per minute, which became 48 cubic feet at atmospheric pressure, and, assuming that eight machines on an average were working together throughout the shift, there was a supply of fresh air amounting to 384 cubic feet per minute. During the charging and the removing of the broken rock also, a jet of air was left open near the forehead.

But though, in the advanced gallery, the ventilation was sufficient, it was not found to be so in the large gallery, as the miners and labourers, 250 metres from the forehead, had been working for some time past in an extremely vitiated atmosphere, at a high temperature. By opening cocks attached to the supply-pipe of compressed air, no doubt, a quantity of fresh air could be obtained, which suddenly expanded, but the waste of power by such a mode of supply would have been such as no engineer would like to sanction. Separate means, therefore, were adopted. In 1864, a horizontal brattice, slightly arched, was placed, extending inwards from each entrance, and dividing the tunnel horizontally. The fresh air passed along the underside, as far as the walling of the tunnel was completed, and the current returned along the upper side, the sectional area of the upper division of the tunnel being about 75 square feet. The brattice was formed of planks, covered with 3 inches of soil, well beaten.

At the south end, the draught was, in the first instance, stimulated by the return current being taken up in a conduit to a chimney, the top of which was not less than 300 feet above the level of the tunnel. When the brattice was completed for about half a mile, the draught was very strong. As the brattice was extended the draught became insufficient, and a furnace was placed in the chimney. Ultimately, a large fan, about 32 feet in diameter, was used to exhaust the air; it produced a strong draught, and the ventilation was good.

As the upward gradient at the south end was only 1 in 2,000, affording practically a level route, the ventilating current met with little opposition from the natural tendency to levitation of lighter gases. At the north end, the gradient against the return current was very steep, being 1 in $45\frac{1}{2}$, and, owing to the increasing height from which the vitiated air-current had to descend, as well as its high temperature, neither the chimney-draught nor the fan-draught in combination with it was sufficient, and it became necessary to apply powerful exhausting pumps. The difficulty of ventilation was greatly increased during the last two years of operation, 1869 and 1870, not only by the increased distances of the work from the entrances, but also by the

greatly increased number of men it was found necessary to employ in enlarging the tunnel, to keep pace with the improved rate of progress in the advanced gallery. Up to the last a sufficient and ample circulation of air was maintained.

It was expected that, on the completion of the tunnel, the difference of level, amounting to 435 feet, between the north and the south ends, would have ensured a steady current of fresh air from north to south, in all states of the weather, and with any probable quantity of traffic. The expectation has not been fulfilled. The ventilation is extremely irregular; the natural draught through it varies extremely. During a few days spent by Mr. Sopwith in the tunnel the air on one day was almost stagnant; and on the following day he could hardly keep his hat on his head. The time at which the ventilation was felt to be worst was when a train was moving up the tunnel from the Modane end, on the gradient of 1 in 45. With a slow current of air, the vapour from the engine, with full steam on, when mounting this gradient, advances slowly and fills the tunnel; and though it is not bad enough seriously to incommode passengers inside the carriages, it is very troublesome to the engine-drivers and to platelayers and others employed in the tunnel; and yet there were in 1873, when these observations were made, only two passenger trains each way, with a certain quantity of goods. Major Beaumont accounts for the air-current from the north through the tunnel by the conical configuration of the mountains at the north end, through which the north wind drives with considerable velocity, and which conduct the current towards the tunnel. The absence of currents from the south end he accounts for by the flatness of the mountains on this side.

A remedy for the want of natural ventilation was in course of application early in 1873. It consisted of a pipe of 20 centimetres, or 8 inches in diameter, laid from end to end of the tunnel, midway between the two lines of rails, which was to be supplied with compressed air by an air-pump at the south end, worked by a water-wheel. Taps were to be fitted to the pipe at short intervals, to be opened as occasion might require by the men at work in the tunnel.

Lighting the tunnel.—The tunnel is lighted by oil-lamps, placed at intervals of 500 metres. Every alternate lamp is marked with the distance in kilometres from the south entrance. At every 1,000 metres there is a lamp-room, 3 metres square. Shelter niches, 1½ metre wide by 1 metre deep, are provided alternately on the two sides of the tunnel, at distances of 50 metres from the south end, and 25 metres from the north end.

Temperature in the tunnel.—In the preliminary stages, and during the first few years of work in the tunnel, no point perhaps excited more interest than the probable heat which would be experienced under a vertical section of so much as 5,281 feet, or 1 mile. The temperature in the tunnel during its construction was less than was anticipated. At a distance of 7,000 metres, or 4⅓ miles, from the south entrance, with a thickness of rock overhead of 5,084 feet, a spring was found, the temperature of which was 84° F.; and this temperature corresponded with observations previously taken in bore-holes driven from the sides of the tunnel. The temperature varied considerably, according to the number of men employed and the quantity of gunpowder consumed. It reached its maximum at the places where the enlargements of the advanced galleries to the full size were being made; and it would have been higher but for the cooling effect of the discharge from the supply-pipe of compressed air, at intervals, which, suddenly expanding and cooling down to the freezing point, lowered the general temperature.

The table on the next page contains some of the observed temperatures in the tunnel at various distances from the south entrance.

Since the completion of the tunnel the temperature of the air in the middle has varied from 80° to 90° F.

Rock-Boring Machinery.—This machinery was in two divisions. First, the machinery 'at the surface,' for compressing atmospheric air and storing the compressed air; secondly, the machinery within the tunnel for boring the rock.

Air-compressors (compresseurs à coup de bélier, or compresseurs à colonne d'eau).—Water was the motive power employed for compressing the air, and the power was, in the first few years of operations, derived from the fall of a column of water. At the south end it was available with a head of 85¼ feet, and it acted on the principle of the hydraulic ram—the water, by the

MONT CENIS TUNNEL.

Observed Temperatures within the Tunnel.

Distance from the south entrance.		Works in progress.		Advanced gallery completed.
		Jan. 16, 1869.	April 17, 1869.	May 20, 1871.
Metres.	Miles.	Fahrenheit.	Fahrenheit.	Fahrenheit.
0 or	0·00	32°	42°	—
500 „	·31	45½	48½	74½°
1,000 „	·62	50	53	75
1,500 „	·93	54	57	76½
2,000 „	1·24	58½	60½	77
2,500 „	1·55	61½	63	78
3,000 „	1·86	64½	66	79
3,500 „	2·18	67½	68	79
4,000 „	2·49	70	70	80
4,500 „	2·80	71½	71	80
5,000 „	3·11	—	—	80
5,500 „	3·42	—	—	80
6,000 „	3·73	—	—	80
First enlargement by manual labour		86½	85½	—
Second do. do.		86	87	—

momentum of its fall, compressing a given quantity of air at each stroke, without the intervention of machinery further than valves for the admission and the escape of the water. There were eleven rams, to each of which the water was conducted from the reservoir above by a pipe, 24 inches in diameter; each ram made from 2½ to 3 strokes per minute, and the air was compressed to 5 atmospheres above atmospheric pressure in a wrought-iron cylindrical vessel, about 5 feet in diameter, having a capacity of 610 cubic feet, connected to the ram. The pressure in the reservoirs was maintained uniform at 6 atmospheres of absolute pressure, by means of a water-pipe communicating from a reservoir with that head of pressure. The inlet-valve was constructed so as to open the passages for the descending water with great rapidity into one limb of a pipe of U form; and for this object the upper end of the spindle was attached to a small piston in a cylinder to which compressed air was admitted; the pressure of the air accelerated the descent of the valve. A ring of caoutchouc, 2 inches thick, received the shock of the descending valve; it crumbled under the shocks, and required to be frequently replaced.

There were two outlet-valves, one of which, for the compressed air, was at the summit of the other limb of the U pipe, communicating with the air-reservoir; the other was at the head or lowest level for the escape of the used water. The inlet and outlet valves for the water were opened and closed by means of a compressed-air engine which turned a shaft with levers for the purpose. A number of comparatively small self-acting clack-valves were fixed on the side of the air-limb of the U pipe, for the inflow of air into that limb, after it had been vacated at each stroke by the used water. The volume of air at atmospheric pressure shut in and compressed for service at each stroke of the ram was measured by a column in the air-limb of the pipe, 14·1 feet high and 2·04 feet in diameter, equal in volume to $2{\cdot}04^2 \times {\cdot}7854 \times 14{\cdot}1 = 46{\cdot}1$ cubic feet.

When compressed to 6 atmospheres of absolute pressure the volume was reduced to $\frac{46{\cdot}1}{6} = 7{\cdot}68$ cubic feet per stroke; and the volume of compressed air stored for $2\frac{1}{2}$ strokes per minute was $7{\cdot}68 \times 2\frac{1}{2} = 19{\cdot}2$ cubic feet per minute.

In this calculation, no allowance has been made for imperfection of performance, and the delivery of air must have been less than that above calculated. The total expenditure of power in the water for generating compressed air was—

$$\frac{2{\cdot}04^2 \times {\cdot}7854 \times 14{\cdot}1 \times 62\tfrac{1}{2}\text{lb.} \times 85\tfrac{1}{4}\text{ feet } \times 2\tfrac{1}{2}\text{ strokes per minute}}{33{,}000} = 18{\cdot}5$$

horse-power.

From these calculations it appears that about 1 horse-power was expended for each cubic foot of compressed air per minute, as calculated.

At the north end, a head of only 20 feet of water was available, though there was an abundant water-supply. M. Sommeiller, desirous to use the same machines as those at Bardonnèche, erected a large cistern, 85 feet above the level of the rams, as at the south end, and pumped the water into it for working them. After a few years' experience of this system, which was needless and costly, M. Sommeiller abandoned it, and substituted horizontal pumps for compressing the air, worked direct from water-wheels by means of cranks from the end of the shaft—two pumps to each wheel. The barrels of the pumps were lined with copper; they were each $21\frac{1}{2}$ inches in diameter, with a stroke which could be varied from $3\frac{1}{2}$ to 5 feet by an

adjustment of the crankpins. The inlet and outlet valves for air both worked under water. Each pump made 12 strokes per minute. The cylinder had open ends, and the water in communication with each end rose and fell with every double stroke of the piston, and by this alternate movement effected the suction of atmospheric air and the discharge of compressed air in two vertical branches alternately. As the variation of pressure on the piston in the course of the stroke, by the increasing resistance of the air undergoing compression, was necessarily very great, a heavy flywheel was fixed inside each water-wheel. This system of compression—'compressure à pompe'—gave better results and was less costly to maintain than the system of the water-column. Mr. Sopwith, in the absence of positive data, considered it probable that to produce 12·662 cubic feet of compressed air per minute—the rate of consumption estimated by him for one perforator—the power required was, with good machinery, 14 horse-power.

No material increase of heat was manifested in the compressing of the air. The immunity in this respect was, no doubt, owing to the constant presence of water, and to the air becoming saturated with watery vapour. Whilst the working parts were wetted at each stroke, the heat evolved by the compression of the air was absorbed and dispersed by the water; and it followed that the only part which became heated, was the outlet-valve for air on the U pipe at the south end, which was not overrun by water as the other parts were. The heat was as great as could be borne by the hand, though it did not reach more than 4 or 5 feet down the pipe which extended from it to the reservoir.

The water-column compressor was, in 1865, abandoned at the south end because the breakages were frequent, and the amount of duty performed did not give satisfaction. The method of the pump-compressor, which had given excellent results at the north end, was substituted at the south end, and it continued to be worked satisfactorily up to the time of the completion of the works.

Supply-pipes.—The compressed air was conveyed from each end through a cast-iron pipe 7⅝ inches in diameter, up to the forehead. The joints of the pipes were made with turned faces, grooved to receive a ring of caoutchouc,

which was tightly screwed up and compressed in the joint. The pipes rested on rollers, carried on stone pillars, and expansion joints were made at intervals outside the tunnel. Tubes of caoutchouc were tried; unsuccessfully.

The loss of pressure, and leakage of air, from the supply-pipes, was found to be inconsiderable. At the south end, with an absolute pressure of 5·70 atmospheres in the reservoir, the pressure at the forehead through a pipe 1,624 metres, or 1 mile 15 yards in length, was only reduced to 5·50 atmospheres, or to 96½ per cent. of the head, whilst eight perforators were actually at work, and expending collectively 64 cubic feet of compressed air per minute.

To ascertain the amount of leakage, at the same time, the reservoirs were filled, also the pipes from them to the forehead of the tunnel, the equalising pressure of water was shut off from the reservoir, and the machines were stopped. At the end of twelve hours, the pressure had only fallen from 6 atmospheres of absolute pressure to 5·8 atmospheres, or to 96⅔ per cent. of the original pressure.

In the middle of the tunnel, through a length of pipe of say, 6,100 metres, or 3¾ miles, the pressure at the surface was reduced, when the perforators were at work, from 6 atmospheres of absolute pressure to 5·7 atmospheres, or to 95 per cent. of the original pressure.

Perforators.—The perforators, drills, or borers were worked and manœuvered entirely by means of compressed air, as follows :—

1. A sudden and violent blow is given by the drill.

2. The drill is withdrawn after the blow is delivered.

3. The drill is slightly turned on its axis after each stroke, that it may strike on a fresh surface at the next stroke.

4. The machine is advanced as the hole is increased in depth.

5. The borings are expelled from the holes by jets of water under pressure.

6. The frame, with the perforators which are carried by it, is withdrawn from the forehead, and advanced towards it, as may be required.

A single-acting compressed-air cylinder and piston, 3 inches in diameter, capable of making a maximum stroke of about 8½ inches, were employed.

The piston-rod, 2·34 inches in diameter, passed out through a stuffing-box at one end of the cylinder; and to the end of the piston-rod the boring-bar, which extended at least 8 feet from the frame of the perforator, was fixed, being in effect a prolongation of the piston-rod. The admission of compressed air to the face of the piston for the forward stroke, and its exhaustion at the end of the stroke, were regulated by means of a slide-valve; whilst the compressed air had constant access to, and occupied the annular space in, the cylinder round the piston-rod. When, therefore, compressed air was admitted to the piston for the forward stroke, it was opposed by the air already in possession of the annular space, and the effective area for the action of propulsive force to make a stroke of the drill, was, in fact, the sectional area of the piston-rod, whilst the counter-pressure on the annular area of the back of the piston effected the return-stroke, withdrawing the drill from the end of the bore, and returning the piston to the head of the cylinder in readiness for the next forward stroke of the piston and the drill.

The movements of the piston were controlled by those of the valve, and therefore, also, the rapidity with which the strokes could be given. For the purpose of effecting, as well as of timing, the reciprocations of the valve, an ordinary double-acting compressed-air engine, having a diameter of 2·638 inches and a stroke of 2·834 inches, was employed as a regulator-engine; it gave motion to a cam-disc on a square shaft, which acted longitudinally on the spindle of the valve, so as to throw open the port to the cylinder, for the admission of air, and subsequently released the valve. The valve thus released by the cam, was simultaneously returned to its initial position by the pressure of the compressed air in the valve-chest on an enlarged portion of the spindle. Thus the required reciprocating movement of the valve was effected, at the required rate of reciprocations—250 per minute—and consequently the drill made 250 strokes per minute.

The piston and its connections were turned round on their axis, to the extent of one-sixteenth or one-twentieth of a revolution, after every stroke. This slight movement was effected by means of a ratchet-wheel, fixed in a shaft in the line of the piston, the end of which was square, and entered into and engaged the piston by a square hole of the same size.

The length of the stroke of the piston could be varied from 2 to 8 or 9 inches ; and it is obvious that, as the bore-hole was deepened, the stroke of the piston and the drill was lengthened, at the same rate of increase, until it became necessary to shift forward the cylinder nearer to its work. As it was desirable that the stroke should be shortened as little as was practicable, the advancement was made by small stages of 1 inch or $1\frac{1}{4}$ inch at a time; this involved a variation only to the same extent in the length of the stroke, which varied from about $7\frac{1}{4}$ or $7\frac{1}{2}$ inches to $8\frac{1}{2}$ inches. The advancing movement was effected by means of a worm on the square shaft just mentioned, which was connected to the head of the percussion-cylinder, and engaged with teeth formed in the longitudinal frame-bars of the machine. The worm became engaged to the square shaft by a clutch, which was put in gear with it by a self-acting clutch-movement, started at the right time by the head of the piston-rod, when the length of stroke had reached its maximum. As the worm revolved in consequence of the ratchet-movement, it gradually thrust forward the percussion-cylinder until it disengaged itself, by its forward movement, from the clutch, which did not advance. Disengaged, the worm ceased to revolve, and with it the percussion-cylinder again became stationary.

When it was required to withdraw the machine from the work, the air was shut off from the regulator-cylinder, the ratchet-motion disconnected, intermediate wheels were slipped into gear, and the regulator-engine started; the worm was turned with a reversed motion, and withdrew the percussion-cylinder with its appendages. A perforator weighed about 6 cwt.

Consumption of compressed air and horse-power of the perforator.—First, for the percussion-cylinder. Taking an average length of stroke of 8 inches, with an area of piston of 7·068 square inches, the net volume of air consumed per stroke, supposing that the air was admitted for the whole of the stroke, was $(7{\cdot}068 \times 8 =)56{\cdot}544$ cubic inches. Adding 10 per cent. for the air that filled the clearance for each stroke, the total volume consumed per stroke was 62·2 cubic inches, and for 250 strokes per minute, single-acting, the consumption was $(62{\cdot}2 \quad 250 =)15{,}550$ cubic inches, or 9 cubic feet per minute. Second, for the regulating cylinder, of which the area was 5·4556 square inches, and the stroke 2·834 inches, the net volume for one double stroke was 30·9224 cubic

inches, supposing that the air had been admitted at full pressure for the whole of the stroke. Adding 5 per cent. for the volume of the clearance at each end of the cylinder, the total volume consumed for one double stroke, was 32·4685 cubic inches, and for 250 strokes per minute, $32·4685 \times 250 = 8,117$ cubic inches $= 4·7$ cubic feet per minute.

Taken together, the total consumption of compressed air per minute was as follows:—

By the percussion-cylinder	9	cubic feet per minute.	
By the regulating-cylinder	4·7	"	"
Total	13·7	"	"
Or, say,	14	"	"

The amount of this estimate is in excess of that of Mr. Sopwith's estimate, which was 12·662 cubic feet per minute. But, applying the ratio of 1 cubic foot of compressed air per minute supplied by 1 horse-power of the compressing machinery, it is proper to adopt the conclusion arrived at by Mr. Sopwith that 14 horse-power of compressing machinery was required for the supply of air of 6 atmospheres absolute pressure, to work one perforator.

The nominal total pressure is here taken as 6 atmospheres, but the actual pressure in the middle of the tunnel was somewhat less, 5·7 atmospheres; the difference of comparative volumes due to the reduction of pressure, would indicate a consumption rather less than that estimated, namely 13·7 cubic feet per minute, but it is not taken into the calculation.

With respect to the horse-power actually exerted by the perforator, the effective pressure was $5·7 - 1 = 4·7$ atmospheres, equivalent, at 14·7 lbs. per square inch, to 69 lbs. per square inch.

Upon the piston of the percussion-cylinder, 7·068 square inches in area, the total effective pressure was equal to $(7·068 \times 69 =)$ 487·7 lbs. and for an average stroke of 8 inches or ·667 feet, 250 times per minute, the actual horse-power amounted to $\frac{487·7 \text{ lbs.} \times ·667 \text{ feet} \times 250 \text{ strokes}}{33,000} = 2·46$ horse-power.

A portion of the forward pressure on the piston was neutralised by the back pressure on the annular area of the back of the piston round the piston-rod, reducing the effective area for the forward stroke, to that of the piston-

rod; but this pressure was continued and exerted during the return stroke, for the purpose of withdrawing the drill; and therefore the performance is equivalent to that effected by the pressure on the whole area of the piston for the forward stroke, as has been assumed in the calculation of actual horse-power.

At the same time the force available for actually propelling the drill is to be calculated upon the sectional area of the piston-rod only, and it amounts to (4·374 square inches × 69 lbs. =) 302 lbs. available force.

Exerted through a space of 8 inches, or two-thirds of a foot, the force performed (302 lbs. × $\frac{2}{3}$ =) 201 foot-pounds of work per stroke, in propelling the drill.

The actual horse-power of the regulator-cylinder is simply found by multiplying the double stroke of the piston by the total effective pressure upon it, and by the number of double strokes per minute, and dividing by 33,000—thus:

$$\frac{5{\cdot}4556 \text{ square inches} \times 69 \text{ lbs.} \times {\cdot}236 \text{ feet} \times 2 \times 250}{33{,}000} = 1{\cdot}32 \text{ horse-power.}$$

The horse-power of the perforator is, then, constituted as follows:—

Percussion-cylinder	2·46 horse-power.
Regulating-cylinder	1·32 „
Total	3·78 „

Which amounts to only 27 per cent., or a little more than a fourth, of the 14 horse-power of compressing machinery required for the supply of the air to one perforator.

Distribution of the Power of the Prime Mover.—To estimate approximately the distribution of the power of the prime mover, by which the supply of compressed air was generated, it may be recalled that the net work done by the compressor in generating compressed air of 6 atmospheres of total pressure was 73 per cent. of the power of the water, of which a portion was consumed in driving a small power-engine that was employed for working the valves. The remaining 27 per cent. was lost on the resistance of friction of the water in the pipes and the valves, in bends, and in the super-elevation above the level, when in a state of rest, of the column of water in the discharging limb of the compressor, in following up and driving the compressed air through its outlet-

valve. Of the 73 per cent. of net work, 27 parts have just been accounted for, in the work of the perforator, worked non-expansively. Had it been worked expansively down to atmospheric pressure, in the actual ratio of 1 to 6, its efficiency would have been increased in the ratio of 1 to 1·69 (the hyperbolic logarithm of 6), to $27 \times 1{\cdot}69 = 45{\cdot}7$ per cent. It may be explained, in passing, that the total work by expansion was measured by the ratio $(1 + 1{\cdot}69) = 2{\cdot}69$, but that a deduction of 1 or unity was due for the back pressure of the atmosphere, which was equal to the initial work of the air; and that $2{\cdot}69 - 1 = 1{\cdot}69$ was the net increase.

Again, there was an allowance made, of 10 per cent. for air to fill the clearance of the percussion-cylinder, and 5 per cent. for the regulating-cylinder; or a mean of, say, 8 per cent. for both cylinders; that is, 8 per cent. of 27 per cent., which represented work by expansion, to the amount of, say, $(27 \times \frac{8}{100}) \times 1{\cdot}69 = 3{\cdot}7$ per cent.

Adding together these two works by expansion, the sum is $45{\cdot}7 + 3{\cdot}7 = 49{\cdot}4$ per cent., leaving 23·6 parts in 73 per cent. consumed by the small engine for working the valves of the compressor, by leakages in the machinery, and for purposes of ventilation.

· The total power of the prime mover was, therefore, distributed thus, in approximate terms :—

COMPRESSED AIR.

Approximate Estimate of Distribution of Total Power of Prime Mover.

Work.	Per cent.	Per cent.	Per cent.
Work done by the perforators . . .	—	27	
Work wasted by the perforators (45·7 − 27)	18·7		
Loss of work caused by clearance in the perforators	3·7		
Work lost and wasted in the perforators .	—	22·4	
Total work consumed in the perforators .	—	—	49·4
Donkey-engines, leakages, and special ventilation	—	—	23·6
Work done in generating compressed air .	—	—	73
Internal resistance of compressors . .	—	—	27
Total work of prime mover . . .	—	—	100

It should be stated that, in the earlier perforators employed, the percussion-cylinder was only 2½ inches in diameter, with a rod of about 2 inches in diameter, and a stroke of from 6 to 8 inches, averaging 7 inches; and that the regulating-cylinder was only 2·375 inches in diameter, with a stroke of 2·375 inches. The net propelling force was only 216 lbs. on the percussion-piston; and it had been remarked that the machines were too small and too light for the work. From the particulars above given it appears that the capacity of the perforators was considerably enlarged; and that the propelling force was increased from 216 to 302 lbs., whilst the average length of stroke was increased from 7 inches to 8 inches. The enlarged capacity of the later perforators, was no doubt of advantage in accelerating the work of drilling and excavation, during the later years of the construction of the tunnel.

An improvement was introduced in the means of producing the rotary movement of the drill. A twist was made in the barrel of the drill-holder, such that, when the drill made its stroke, it advanced in a straight line, but in returning, it was caused, by a simple arrangement, to revolve slightly on its axis. Thus the revolution of the drill was effected, and the machinery was simplified.

Washing out the borings.—The injection of a stream of water to wash out the débris, as the drill advanced into the bore, though it was not absolutely necessary, no doubt tended to accelerate the work. About forty of the holes in the forehead were made without the use of water, for it was found that the use of water in the upper part of the heading was distressing to the workmen engaged on the lower holes. The backward splash of the water, mixed with the débris from the upper holes, rendered the performance of their duties a matter of great difficulty for any length of time.

More recently, since the completion of the tunnel, further improvements were made in the perforator of M. Sommeiller, a notice of which will be found in the account of the St. Gothard Tunnel. A third cylinder was introduced, which kept the percussion-cylinder up to its work, and withdrew it immediately when it became necessary to change a drill—an operation which required some minutes to be executed; and the whole of the mechanism previously applied for this purpose, comprising the worm and other parts, was to be

suppressed. There was evident need for simplification of details, for the machines were liable to frequent derangement. Usually, after eight or ten shifts, or after boring from sixty to eighty holes, a perforator needed to be repacked, and probably required some working part to be repaired or renewed. It was ascertained that, at Mont Cenis, in order to maintain a given number of perforators in constant use, a stock of four times that number of perforators was required to be provided—showing that not more than 25 per cent. could be maintained in constant use, the remainder being in store or under repair.

Carriage for perforators.—The perforators working at each forehead, to the extent of eleven perforators at the north end, and nine at the south end, in the earlier operations, were mounted on a wrought-iron frame or carriage, which was moved on rails close to the forehead. The frame with its mountings complete, including bars, crossbars, adjusting screws, &c., weighed about 15 tons. A small reservoir placed on the hinder part of the frame, received an open supply of compressed air from the main, with which it was connected by an india-rubber tube; and it supplied the air required for each perforator through branch tubes 2 inches in diameter. Each perforator could be made to work at any desirable inclination; but as, in working at a considerable angle, it was likely to interfere with the efficient working of the others, the holes were bored in directions nearly horizontal. If not all so well placed as they might have been, a sufficient number of holes could nevertheless be bored; and it was of importance at Mont Cenis that the rock should be broken away in small pieces that could be readily removed. A species of tender was provided, behind the carriage, bearing wrought-iron vessels filled with water, kept under pressure of 5 atmospheres of compressed air, for supplying the jets of water to clear the bore-holes and keep the drills cool.

The frame was provided with an engine, worked by compressed air, for advancing it towards, and withdrawing it from, the forehead. At the completion of a shift, it was withdrawn to a distance of from 60 to 100 yards, for shelter behind the doors which have already been noticed, when the charges were to be fired; when required again, it could be moved up to the forehead in two or three minutes, and, within from five to ten minutes, all the perforators were again set to work. The great length of the boring-bars,

which permitted the frame to be placed from 6 to 8 feet clear of the forehead, facilitated the adjustment of the bars to their work. The floor of the excavation was generally uneven, so much so that it would not have been possible, without dressing the bottom, to bring the frame close up to the forehead; besides, the position of the line of rails was frequently altered.

Labour and Cost.—For each period of working, or shift, 80 holes were bored in the forehead of the advanced gallery. When these were completed, the perforators and their carriage were withdrawn, and another set of men charged and fired the holes; after whom, a third set of men removed the rock broken down. The time required to work a complete shift, in 1863, was estimated by Mr. Sopwith as follows:—

For drilling	6 to 8 hours.
For charging and firing	1½ ,, 2 ,,
For removing the broken rock . . .	3 ,, 5 ,,
Total	10½ to 15 ,,

Being less than two complete shifts in twenty-four hours. In June 1863, at the south end, during twenty-seven working days of twenty-four hours, forty-six shifts were worked, being at the rate of 1·92 shifts per day.

Number of Men employed within the tunnel.—In the advanced gallery at the north end, the machinists worked a shift of from six to eight hours, and were relieved by the chargers and the clearers or men who removed the broken rock. A second set of machinists followed, but they were succeeded by the same set of chargers and clearers as preceded them, who worked double turns, for their work did not last so long as that of the machinists. There were therefore, at the north end—

Two sets of machinists, 44 per shift—in all	88 men.
One set of chargers . . . . ,,	9 ,,
One set of clearers . . . . ,,	30 ,,
Total in the advanced gallery. . .	127 ,,

The following statement shows the composition of these sets of men, with the rate of wages paid to them:—

	Per day. f. c.	f. c.
MACHINISTS FOR TWO SHIFTS :—		
2 Foremen	7 0	
10 Adjusters or fitters, one to every two machines, for fixing, withdrawing, and making small repairs	5 0	
20 Miners, to guide and change tools	2 6 to	2 9
20 Labourers	2 0 to	2 5
22 Labourers, one for the hinder end of each machine, to open and shut valves, as directed by the miner at the head of the machine, and stop or set to work the machine	2 0 to	2 5
10 Boys, to oil machinery	1 5	
2 Mechanics, for attaching the pressure-pipes to machines	2 5	
2 Boys, for oil-lamps	1 5	
88, or 44 per shift.		
CHARGERS :—		
6 Miners, for two shifts	4 2	
3 Boys	1 5	
9		
CLEARERS :—		
1 Foreman, for two shifts	4 0	
2 Miners, to bring down loose pieces, &c.	4 0	
27 Labourers	2 0 to	2 5
30		

An inducement to work was given, in the form of a premium upon more than a certain progress per day in the advanced gallery. The standard of progress varied with the nature of the rock; in 1863, it was 1 metre per day, for which a day's wages was paid.

For 1·1 metre per day	1·1 day's wages were paid.
1·25 ,, ,,	1·25 ,, ,,
1·3 ,, ,,	1·3 ,, ,,
1·4 ,, ,,	1·4 ,, ,,

For enlarging the tunnel there were three sets of miners for twenty-four hours, and two sets of masons, all working 8-hour shifts—in all 344 men.

Number of men employed at the surface.—The stone-dressers, quarrymen, blacksmiths, and labourers were 229 in number. At the establishment below, workshops, machinery, canals, &c., 240 were employed, and, in addition, there

were from 150 to 200 'occasional' employés, who were nearly always employed.

The total number of all classes employed at Modane, was as follows:—

	Employés.	
Within the tunnel—Advanced gallery	127	
Enlarging	344	
		471
At the surface—Stone-dressers, &c.	229	
In workshop, &c.	240	
		429
Occasional		200
Total employed at the north end		1,100
The total number employed at the south end (1,200 to 1,400), say		1,400
Total employed on the works		2,540

During the latest stages of the work, upwards of 4,000 persons were employed directly on the tunnel. At the north end, the total number employed was 1,990; at the south end, the number employed was generally in excess of this number, The following was the composition of the employés at the north end:—

	Employés.	
In the advanced gallery—		
Adjusters	13	
Miners	14	
Labourers	140	
Boys	13	
		180
Enlargement by manual labour—		
Miners	510	
Labourers	180	
Boys	30	
		720
Masonry—		
Masons and stone-dressers	58	
Labourers	170	
Boys	52	
		280

		Employés.
Manufactories, machinery, stores, and surface works—		
Smiths, joiners, fitters, &c.	120	
Labourers	440	
Boys	10	
		570
Overseers, foremen, clerks, &c.		60
Platelayers, transport of materials, &c.		180
Total employed on the works		1,990
Horse-power of machines—		H.P.
Hydraulic wheels		480
Ventilating machines		300
Sundry		80
Total horse-power of machinery		860
Horses employed in clearing away broken rock		80

Comparative cost of mining by hand labour and by machinery.—Mr. Sopwith states that, at the north end, previous to the employment of the machine, the cost of driving the advanced gallery, 10 feet square, by hand labour was as follows:—36 miners in three shifts per day, 12 men in each shift, having been employed:—

	£	s.	d.
36 Miners, at 2*s*. 6*d*. per day	4	10	0
Tools, gunpowder, and light	1	10	0
Total	6	0	0

Applying the cost to the average daily progress made at the north end in 1862, the last year of hand labour, which was 2·18 feet per day, the cost of advancement, above calculated, was at the rate of 8*l*. 5*s*. 2*d*. per lineal yard.

In estimating the cost of mining by machine, Mr. Sopwith, using the data supplied in June 1863, found the cost for labour and material in the advanced gallery, as follows:—

	£	s.	d.
Miners and machinists, per shift	4	14	8
Tools, gunpowder, and light	3	10	0
Per shift	8	4	8

which, for an advancement of 2·769 feet per shift, was at the rate of 8*l.* 18*s.* 4*d.* per lineal yard.

There was, in addition, a charge for machinery within and without the tunnel; and having assumed, for the sake of forming a general comparison, that the motive power for working the compressors was steam, Mr. Sopwith estimates the other expenses thus:—

	£	s.	d.
Engineers and stokers, 15*s.*; coal, 4 tons, 2*l.* per day	2	15	0
240 men, employed in the shops and about the machinery at the north end, say this was reduced to 120, at 3*s.* per day	18	0	0
Steam-power to drive machinery, &c., for coal and attendance, per day	1	10	0
Maintenance of machinery, 20 per cent. on 20,000*l.*, per day	5	10	0
Cost, as in June 1863, per day, for an advancement of 4·72 feet	27	15	0
Equivalent to, per lineal yard	17	12	9
Add mining charge, as above	8	18	4
Total cost, per lineal yard, by machine	26	11	1

As compared with a cost of 8*l.* 5*s.* 2*d.* per lineal yard, by hand labour.

From these estimates it appears that, by machinery, as compared with hand labour, the rate of progress was more than doubled, and the cost per yard was more than tripled.

If the greater progress, 6·8 lineal feet per day, made at the north end by machine labour in 1870, the last year of operations, be compared, it is more than three times the latest progress by hand labour. On the contrary, the number of employés, 180, in the advanced gallery, was nearly a half greater than in 1863. In the absence of data for accurately completing the comparison, it may suffice for the present to assume that the greater part of the charges, as estimated for June 1863, would be stationary; that the total charge per day would be about 42*l.* per day, equivalent to 18*l.* 10*s.* per lineal yard. On this assumption, it would appear that whilst, ultimately, the rate of progress was tripled by machine, as compared with hand labour, the cost per lineal yard was fully doubled.

Mr. Sopwith made a rough estimate of the total cost for labour and

materials in the construction of the tunnel, in 1863, by taking 2,500 employés, at an average rate of 2*s*. per day, to construct 3 lineal yards per day. The calculation may be repeated for the last year of construction, 1870, when there were 4,000 employés, at, say, 2*s*. per day, constructing 5 lineal yards per day; as follows:—

		1863	1870.
		£	£
Cost for labour, per lineal yard		85	80
„ Materials „	say	40	40
Cost for labour and materials		125	120

Showing the cost, 125*l*. in 1863, and 120*l*. in 1870, per lineal yard.

The preliminary estimate of the total cost of constructing the tunnel amounted to 2,600,000*l*., equivalent to 194*l*. per lineal yard. It is supposed that the actual cost amounted to 3,000,000*l*., which is equivalent to 224*l*. per yard.

In the end of 1867, the construction of the remainder of the tunnel, 4,387 metres, was sublet to MM. Sommeiller and Grattoni at the price of 4,617 francs per lineal metre, equivalent to 167*l*. 12*s*. per lineal yard; and it was conjectured that the actual cost to the contractors amounted to about 74*l*. per lineal yard.

In this connection, the following particulars of cost, in English measures, may be quoted from M. de Parville, in the 'Annuaire du Cosmos,' 1863:—

Excavation, per lineal yard	71¾ cubic yards.	
Masonry „ „	18 to 19 „	
	South end.	North end.
	£ *s*. *d*. £ *s*. *d*.	£ *s*. *d*.
Cost of excavation per cubic yard, removal of rock included	0 7 11 to 0 10 4	0 12 2
Cost of masonry per cubic yard	1 0 8	0 18 3
Cost of excavation, removal of rock, masonry, all included, per lineal yard	39 18 7	47 3 10

These data may be taken for what they are worth, though they are hardly consistent with each other.

CHAPTER XXIV.

TUNNELLING IN HARD ROCK.

ST. GOTHARD TUNNEL.

THE St. Gothard Tunnel through the Alps was projected, and is now in course of construction, to complete the link of connection between the Swiss system of railways and the railways of Upper Italy, in the valley of the Tessino. The tunnel passes through the Alps between Goeschenen on the north side and Airolo on the south side. It is to be constructed for two lines of way on the 4 feet 8½ inch gauge, and is to be straight throughout, with the exception of a length of 145 metres at the south end, which is to be a portion of a curve of 300 metres radius to connect the tunnel with the station at Airolo. The tunnel is likewise to be connected by a curve with the station at Goeschenen; but the curve will be wholly beyond the tunnel.

For facility of construction the tunnel will, in the first instance, be cut perfectly straight through to the surface at the south end.

The tunnel is to be 14,900 metres in length, and the total distance between the stations of Goeschenen and Airolo is 15,037 metres, distributed thus:—

	Metres.
Goeschenen station to the north end of the tunnel	25
Length of the tunnel	14,900
Airolo station to the south end of the tunnel	112
Total distance between the stations	15,037
The total length of straight tunnel constructed will, in the first instance, be	14,920
Of which the prolongation, for purposes of construction, will be	165

	Metres.
The remainder, by deducting the prolongation, is to be—	
The length of the permanent straight portion of the tunnel	14,755
Add the length of the curvilineal portion	145
Length of the tunnel, as completed	14,900

Or 16,295 yards, or 9·2585 miles.

With respect to the levels and the gradients to which the tunnel is formed :—

	Metres.
Airolo station is above the level of the sea	1,145
Goeschenen station „ „ „	1,109
Difference of level, Airolo above Goeschenen	36

Or 39·37 yards. The line rises from both stations towards a summit level, 180 metres in length, within the tunnel, which stands :—

	Metres.
Above the level of the sea	1152·40
Above the level of Goeschenen station (47·46 yards)	43·40
„ „ Airolo „ (8·09 „)	7·40

The summit-level and the gradients are distributed as follows :—

	Metres.
Goeschenen station to summit level	7,457
Length of summit level	180
Summit level to Airolo station	7,400
Goeschenen station to Airolo station	15,037

The northern gradient is, therefore, at the rate of 5·82 in 1,000, or 1 in 172 ; and the southern gradient is at the rate of 1 in 1,000. The formation of the gradients, falling from a summit within the tunnel, was designed, of course, for the purpose of providing a fall for the waters of infiltration from both faces of the tunnel whilst it is in process of construction ; and the flatter gradient, 1 in 1,000, was fixed upon as that which would be just sufficient to ensure the natural flow of the water towards the mouth of the tunnel.

Finally, the profile of the tunnel alone is composed as follows :—

	Metres.		Yards.
Rising gradient from the north end, 1 in 172	7,432	or	8127·8
Summit level	180	„	196·9
Falling gradient towards the south end, 1 in 1,000	7,288	„	7970·3
	14,900	„	16,295

Geological structure of the St. Gothard.—According to the observations and deductions of Professor Fritsch, of Frankfort, the principal mass of the chain to be traversed is composed of gneiss, rich in mica, passing into mica-schist, and alternating with gneiss and hornblende-schist. The beds of rock are disposed in the form of a fan, a characteristic of Alpine formations generally, in such a manner that, towards the north end of the section, the beds are inclined southwards; towards the south end, northwards; and in the middle they are vertical. The detailed estimation of the varieties and thicknesses of the formations, in their order from north to south, are subjoined :—

	Metres.
Granitic gneiss, more or less homogeneous	2,200
Gneiss, more or less schistous	450
Crystalline limestone, with grey marble	350
Micaceous schist, passing to gneiss	1,300
Gneiss, rich in mica, passing into mica-schist	6,600
Mica-schist, with more or less hornblende	1,600
Gneiss, more or less schistous	270
Mica-schist, with veins of quartz	800
Hornblende-schist	1,250
Dolomite, gypsum, &c.	100
Approximate length of the tunnel	14,920

Form and construction of the tunnel.—According to the terms of the specification and contract, the tunnel is to be formed to the internal section shown in Plate XIX.; and is to have the same sectional dimensions as that of Mont Cenis; that is, 6 metres, or 19·68 feet high, from the level of the sleepers to the soffit of the arch; 7·60 metres, or 24·93 feet wide at the level of the sleepers; and 8 metres, or 26·24 feet wide at the springing of the arch, which is 2 metres, or 6·56 feet above the level of the sleepers. The

arch is to be a complete semicircle of 4 metres radius. The sides, or walls, are to be curved to a radius of 10·10 metres, or 33·13 feet. The floor, when formed of the solid rock, is to be slightly troughed, being ·70 metre or 27·6 inches below the level of the sleepers at the centre, and ·50 metre, or 19·7 inches below, at the sides.

Several types of sections are specified to be adopted in the construction of the tunnel, according to the nature of the rock that is traversed, as follows:—

In rock that is very solid and fissureless, the tunnel is to be cut to the exact section, without any masonry.

Or it may be partially walled where necessary.

In solid rock, with fissures, a segmental arch is to be turned to a radius of 4·70 metres, or 15·4 feet, with a span of 8 metres, and a thickness of from ·5 to ·6 metre, or 19·7 to 23·6 inches. The sides, if bare, are to be cut to a radius of 4 metres at the upper part; if walled, to be finished vertical to a clear width of 8 metres.

Or the arch may be pointed, to radii of 6·7 metres.

In less solid rock, arched and walled, the arch is to be circular, turned to a radius of 4 metres, and from ·45 to ·75 metre, or 17·7 to 29·6 inches, thick.

In loose rock, the tunnel is to be completely lined, with a semicircular arch, and side walls, of from ·60 to ·75 metre, or 23·6 to 29·6 inches in thickness; and an invert ·75 metre, or 29·6 inches thick—near the centre—with a versed sine of 1·5 metre, or 4·92 feet.

A culvert, 1 metre, or 3·28 feet square, is to be formed in the floor of the tunnel.

The contract for the construction of the tunnel was let to M. L. Favre, on August 7, 1872, to be completed within eight years. The table on next page gives the particulars of the quantities, prices, and total cost.

Observatories are established at Goeschenen and Airolo for regulating the direction of the tunnel. At Goeschenen, a gallery, 114 metres long, has been cut through the rock which separates the Goeschenen Reuss from the St. Gothard Reuss, to admit of the construction of the observatory on the left bank of the Goeschenen, so as to prolong the line of sight to the mouth of the

CONTRACT PRICES FOR THE CONSTRUCTION OF ST. GOTHARD TUNNEL.

M. L. Favre, Contractor.

Description of work.	Lineal metres.	Rate.	Amount.	Lineal yards.	Rate at 25 francs to the £.	Amount.
I.—Fixed Cost.	Metres.	Francs.	Francs.	Yards.	£	£
1. Tunnel of direction at Airolo	145	1,500	217,500	158·6	54·4	8,631
2. Excavation of the tunnel .	14,900	2,800	41,720,000	16,295	101·6	1,665,500
3. Ballast and sidewalks . . .	14,900	22	327,800	16,295	1·6s.	13,008
4. Laying the double way and maintenance (2 × 14,900) .	29,800	4	119,200	32,590	2·9s.	4,730
II.—Variable Cost.	Cubic metres.			Cubic yards.		
1. Ashlar masonry	40,000	75	3,000,000	52,320	£2·27	119,050
	Sq. metres.			Square yards.		
2. Facing work	60,000	20	1,200,000	78,480	13·38	47,620
	Cubic metres.			Cubic yards.		
3. Ordinary masonry	30,000	40	1,200,000	39,240	1·21	47,620
4. Masonry of the niches (120)	—	165	19,800	—	6·55	786
Total cost of the works			47,804,300	—		1,896,945
Equivalent to, per lineal metre			3,208	Per lineal yard . .		£116 8s.

tunnel to 590 metres, or 645 yards. At Airolo, the length of the line of sight is limited to 348 metres, or 380½ yards, by the south flank of the mountain, on the right bank of the Tessino.

Commencement of the work.—After some preliminary clearing operations had been completed by the railway company, M. Favre commenced the work of his contract, at Airolo on September 13, and at Goeschenen on October 24, 1872. The date of commencement is recognised as October 1, 1872, and the contractor is under engagements to complete the tunnel by October 1, 1880.

System of construction.—The tunnel is being constructed on the Belgian or French system, as it is called, illustrated by Plate XIX., showing the successive stages of progress. A heading, or advanced gallery, is driven at the upper part of the tunnel, from each end, at such a level that the roof of the heading becomes, in fact, a portion of the roof of the excavation for the tunnel. The enlargement of the tunnel, from the heading, is proceeded with laterally and downwards. The heading was excavated by hand for the first six or seven months; after which time it was, and it is now, driven exclusively by means of perforating machines, or rock-drills, worked by compressed air. The enlargement was until recently (1875) effected partly by hand labour and

partly by machine labour; but it is now performed altogether by machine labour.

Nature of the material, and contingencies.—The nature of the rock that has hitherto (January 31, 1876) been traversed, at both ends, fairly justifies the anticipations of Mr. Fritsch. The material at one end differed widely in physical structure from the material at the other end. At the north end, the material from the commencement, and for a thickness of 2,003 metres, or 2,185 yards, which was penetrated by the end of April 1875, was a hard, resisting granitic gneiss, varying occasionally into gneiss and gneiss-mica-schist, and closing with the gneiss of the Finsteraarhorn. Before arriving at 2,002 metres, the point of transition was arrived at between the gneiss and the metamorphic sedimentary rocks of the valley of Urseren, of which the first beds were found to be gneissous mica-schist. At the point of transition, the gneiss was rich in mica; and the new formations were found to be perfectly dry at the joints of the rocks. The rock was practically dry from end to end of the excavation; and, though it was fissured in many places, it stood well when excavated, and no timbering was required for its support. At distances from 200 to 330 yards further on, partially decomposed argillaceous rock was met with, in strata, the thickest of which was 20 feet in thickness. But the strata were too thin to give rise to pressure, and though there were trifling leakages, in the form of rain, from the roof, the progress of the work was not hindered. Between 2,600 and 2,800 metres, the calcareous beds of the valley of Urseren were traversed, following which, gneiss, rich in mica, pliable and weak, was excavated by hand labour, and required to be strongly timbered. The progress made at the front, under the circumstances, was only 1 metre per day.

At the south end, on the contrary, the dominant formation consisted of mica-schist, very variable in quality, with numerous fissures, through which water passed into the tunnel in large volumes. At the first penetration, earth mixed with sand and gravel was met with, followed by gypsum, talc, mica-schist, and dolomite, till a depth of 86 metres, or 94 yards, was reached, when progress was temporarily arrested by a bed, 13 feet thick, of débris of dolomite and mica-schist, with blocks of quartz intermixed. Water was discharged

at the rate of 420 gallons per minute, and it brought down with it a mass of the débris into the tunnel. After having, with much difficulty, traversed this loose bed, the miners again came up with mica-schist, charged, as before, with water for a distance of 416 metres, or 454 yards, from the mouth, numerously fissured, and interrupted by beds of clay and many other kinds of rock, which formed conduits for the water. From these openings the water was projected under considerable pressure, and delivered at the rate of 2,640 gallons per minute.

The discharge of water at the front was increased as mica predominated in the mica-schist, as quartz decreased, and as thin beds of clay separated the beds of mica-chist; and, of course, when all these circumstances were united, the consistency of the rock was destroyed. The work was arrested for some days by a spring which appeared at 165 metres, or 180 yards, and delivered 1,000 gallons per minute. The rock was torn up by the violence of the jet, and the flood was thus still more increased.

In advancing further to a depth of 596 metres, or 650 yards, the quality of the mica-schist varied frequently, alternating into quartzose, hornblende, and calcareous schist, when the discharged water amounted to from 2,400 to 2,700 gallons per minute. During the next stage of advance, to a depth of 766 metres, or 835 yards, the rock was for some distance so friable that hand labour was substituted for machine labour in excavation. Quartzose schist and calcareous mica-schist were passed through, fissured in all directions, with an abundant discharge of water. But it was in penetrating the next section, to a depth of 926 metres, or 1,010 yards, that the greatest and most violent discharge of water took place. The rock was hornblende, with beds of mica-schist, and for a depth of 10 feet, at one place, the miners worked amongst powerful jets of water crossing each other, and delivered at the rate of 3,000 gallons per minute. This troublesome section was succeeded by a section of hornblende rock and mica-schist with quartzite, nearly all quite dry, when a total depth of 1,100 metres, or 1,200 yards, was attained. Then followed a variety of quartzose mica-schist, containing several beds of hornblende decomposed into mica. With similar variations, a depth of 1,220 metres, or 1,330 yards, was reached, in a greyish-green mica-schist, rich in

hornblende, and pervaded by chalk in small quantities in the form of veins, bands, and swellings, which rendered the rock subject to decomposition when exposed to the air. About this point, an immense jet of water, nearly 1½ foot wide, was suddenly projected into the tunnel, striking the roof of the gallery, at a distance of 16 feet from the face, with a force sufficient to knock down anyone who came in its way. It was estimated that this jet alone delivered nearly 210 gallons per minute. A little further on, another jet, about ½ inch thick and 1 foot wide, sprung out into the gallery, forming a cascade. At this time, the total quantity of water that ran from the tunnel amounted to 3,000 gallons per minute. At 1,250 metres, or 1,360 yards, 3,120 gallons per minute was discharged.

At last, an abatement, and practically a cessation, of the discharge of water from the front took place. Through grey mica-schist and hornblende, with variations, a depth of 1,450 metres, or 1,580 yards, was attained by the end of January 1875, when very little water was discharged. By the end of March, when 1,632 metres, or 1,780 yards, was reached, the total flow of water from the tunnel was 3,000 gallons per minute—rather less than the flow when the gallery was more than 400 yards shorter. The flow subsequently increased, as the heading was advanced, until, when 2,288 metres, or 2,500 yards, was reached, the combined flow rose to 4,600 gallons per minute.

Whilst the rock met with at the north end was, for the most part, sufficiently solid and resisting to stand unsupported when excavated, at the south end, on the contrary, for the first 266 metres, or 290 yards, traversing earth, sand, gravel, sandstone, fissury mica-schist, cut up with strata of clay, the gallery was continuously and solidly timbered. Beyond this distance, timbering was only required at particular points where the rock was more or less decomposed, and had become argillaceous.

Method of excavating the headings.—The dimensions which have been found most advantageous for the headings are about 2·5 metres high, by 2·5 metres wide (8 feet 2½ inches square), giving a frontal area of 67¼ square feet. In hard rock, with dynamite for the explosive material, from 24 to 26 holes are bored in the face of the heading, five in a row. The holes are from 24 to 28 inches apart, excepting three holes arranged triangularly near the centre;

these are commenced at 16 inches apart, and converge internally until they finish at a distance of 4 inches apart at the bottom. The holes immediately surrounding the centre holes are bored horizontally and perpendicular to the face, whilst the holes at the sides, top, and bottom diverge in direction in order to clear out the new front of the heading to the full standard size. From experience, it is found that the best depth of hole for blasting with dynamite is from 3·91 to 3·94 feet (1·10 to 1·20 metre). It is not practicable to bore the holes strictly uniform in diameter, as there is unavoidable lateral wear of the drills. The holes are, therefore, bored with four sizes of jumper, of successively diminishing diameters, changed from one to the other: namely, 48, 42, 38, 32 millimetres, or 1·89, 1·65, 1·50, 1·26 inch, with each of which about 10 inches in depth is bored. The holes are, then, 1·89 inch in diameter at the mouth, and 1·26 inch at the bottom.

The dynamite is made up into cartridges of 27 millimetres, or 1·06 inch in diameter, containing from 1½ lbs. to 4 lbs. of explosive. It is necessary, for the most part, to enclose the cartridges in sheet-iron cases to keep the charge in good condition when placed in watery bore-holes; and, in general, cartridges exposed to water are fitted with two matches.

The perforating machines employed in the heading are six in number, mounted on a carriage which is placed on a line of rails of 1 metre gauge, laid to the front. A tender containing a supply of water for clearing the bore-holes, together with a waggon which carries a supply of fresh boring-bars, are in attendance behind the perforator-carriage, on the same line of rails. The carriage is advanced to a position at about 5 feet from the forehead, where it is fixed; the supply-pipe with compressed air is connected to the carriage, and the work of perforation is commenced. The 'attack' is so disposed as to admit of easy access between the drills, that they may be correctly pointed. The process of perforation lasts from 2½ to 3 hours. When the last holes are bored, the charging is commenced, whilst the carriage with its accessories are withdrawn to a distance of about 90 yards from the forehead, and turned into a siding in the enlarged part of the tunnel, where they are so disposed that the tender and the waggon are placed in front of the carriage, so as to shield it from flying fragments of rock that may chance to come that way.

The charging of the bore-holes is performed in three stages: 1. The three holes at the centre receive charges each of 800 grammes, or 28·3 ounces, of dynamite, which occupy two-thirds of the depth, and the matches are lighted. The three charges are susceptible of percussive action from each other by reason of their proximity, and are therefore exploded simultaneously. One single match in one of the holes would suffice for the explosion of all the three charges; but it is preferred to fix and to light all three matches, in case of a miss-fire of one or two of them. The explosion opens a conical cavity in the rock, which facilitates the discharge of the other 'mines' or holes when exploded. 2. After this preliminary explosion, the whole of the remaining holes are charged, excepting the lowest row, with charges of 500 grammes, or 17·6 ounces of dynamite. In order that they may be exploded successively from the centre outwards—not simultaneously—the matches are collected into a bunch at the middle of the front, and are cut square off; the matches which are more nearly central being of course the shorter; and they are all lit. The charges next the centre are the first to explode; the others following in succession towards the outer sides. The second explosion over, iron waggons, having a capacity of $\frac{1}{3}$ cubic metre, or 12 cubic feet, which are held in readiness, are brought up to the front and loaded with the rock which is blown off; the loosened rock is picked off, and collected in baskets and put into the waggons, and removed. 3. The remaining row of holes, next the floor, is charged with 500 grammes of dynamite to each hole, and discharged. Thus the blasting is completed for one shift. There are two levels in the tunnel, an upper and a lower, with distinct lines of rail. The contents of the upper train of waggons are discharged by a shoot into waggons on the lower level, having a capacity of 1 cubic metre, or 35 cubic feet, in which it is conveyed away by a compressed-air locomotive to the entrance.

A hydraulic hoist is employed to raise and lower the machinery and tools for the upper excavations, and the cut stone and other work for the construction of the arch. It is capable of lifting 4 tons to a height of 14 feet—the difference of level of the rails. The platform of the hoist is about 6 feet wide by $11\frac{1}{2}$ feet in length, and it is raised by means of two 6-inch hydraulic cylinders, single-acting, through the medium of pulley

blocks, 3 chains deep, with a pressure of thirty atmospheres of water. The supply of water for working the elevator is obtained by an accumulator loaded by means of a compressed-air engine of 1 horse-power, consuming 5 cubic feet of air at five atmospheres per minute. The accumulator consists of a vertical ram or plunger, 12 inches in diameter, having a range of 5½ feet within a cylinder, and loaded with 20 tons of lead ingots. The total pressure within the cylinder, including the weight of the ram, is about 20½ tons. The quantity of water taken in and stored under pressure at one stroke of the ram is 4·46 cubic feet, which is sufficient for one lift.

The quantity of rock blown out per shift averages about 1 metre, or 3·28 feet, in depth, and 6·25 cubic metres, or 8⅓ cubic yards, in bulk.

The quantity of dynamite consumed per shift is as follows:—

	Grammes.		Ounces.
For 3 central holes, each 800 grammes (28·3 ounces) . .	2,400	or	85
For 23 other holes, each 500 grammes	11,500	„	405
Total	13,900	„	490

Say 14 kilogrammes, or 30·6 lbs. per shift, being at the rate of 3·7 lbs. per cubic yard.

When the rock is soft, or when the 'barres' are vertical and perpendicular to the line of the gallery, fewer holes are required; one central hole may suffice, instead of three.

Whilst the charging and discharging, and the removal of the broken rock, are in progress, the perforators which have been withdrawn are cleaned, and small repairs that may be needed are executed.

When the heading is cleared, the line of rails is extended up to the new front, and the perforating train is brought up and re-adjusted to bore into the new forehead.

Order and progress of the construction.—The consecutive stages of the construction of the tunnel are shown in Plate XIX., representing the north end and the south end respectively—the advanced gallery, the enlargement of the gallery, the building of the arch, the removal of the core of rock, and the building of the side walls and the construction of the drain in the

middle of the floor. In tracing the successive developments of the excavation, it is shown that in the removal of the 'strosse,' core, or lower body of rock, below the region of the arch, different methods of procedure are adopted for the north and the south ends. At the north end, a 'cunette,' or central trench, 2½ metres, or 8 feet 2 inches wide, is excavated down to the floor of the tunnel; and, next, the rock is excavated successively to the right and to the left, to form the permanent walls of the tunnel. At the south end, the rock is entirely removed on one side of the axis of the tunnel, to give room for the building of the wall in masonry; and, next, it is entirely removed from the other side, for the building of the opposite wall.

After the luminous account of the progress of excavation, timbering, and building of tunnels, given by Mr. Simms, it is not needful to dwell upon the details of these operations now. The timbering that was applied for the south end is very clearly shown in Plate XIX. The centering consists of segmental flitches, about 12 inches wide, breaking joint, and bolted together to form an arch. The poling-boards are left in their places at the back of the arch, and the interspaces filled in.

The advanced gallery at the north end is rectangular in section. It was in the first portion made 2·4 metres wide, by 2·5 metres high, giving an area of forehead equal to 6 square metres; or 7 feet 10½ inches wide by 8 feet 2½ inches high, with a frontal area of 66 square feet. It was mined by hand labour until the end of March 1873, when it had attained a depth of 87·2 metres, or 95 yards. Reckoning the performance at 82·4 metres, or 90 yards, as from December 1, 1872, when the work got well in course, the average rate of progress by hand labour was 2·23 feet per day.

In the beginning of April 1873, mechanical perforation was substituted for hand labour in the advanced gallery, and for this purpose the rock-drills of MM. Dubois and François, of Seraing, were employed. Six drills were mounted on one carriage, and operated all together on the forehead. The bore-holes were 35 centimetres, or 1·4 inch, in diameter, and were cut to a depth ordinarily of 1 metre. In April, 1·5 lineal metres were cut by hand labour, and 28·9 metres by machine. In May, 42·5 metres were pierced, and the progress further improved in the following months, until, in March 1874,

with Dubois and François' machines, 82·1 metres, or 89½ yards, were cut, equivalent to 2·9 feet per day. These machines were employed at the front until May 8, 1874, when they were replaced by six of Ferroux's perforators. They had been at work continuously for upwards of thirteen months, or for 400 days, during which time the heading was advanced by these means from a depth of 88·7 metres to 897 metres, showing a net advance equal to 808·3 metres, or 882 lineal yards, being at the rate of 6·63 feet per day. Selecting the work of the last six months of the period ending April 30, 1874, 374·1 metres, or 408 lineal yards, were perforated in 181 days—at the rate of 6·76 feet per day.

Meantime, the area of the front was enlarged to 6·4 square metres. The number of holes bored in the front averaged 26 and 24 for each shift; the most common average was 24. The average depth of the holes was 1 metre except at about 800 metres deep, where the rock became softer, when the depth, for a short interval, was increased to 1·8 metre, or 6 feet.

Six of Ferroux's perforators were mounted on the carriage and started at the front, as was stated, on May 8, 1874, and Ferroux's drills have been continuously employed at the north end to the present time (1876). The area of the front, or the sectional area of the gallery, was further enlarged, during this period, to 6·8 square metres, or 67 square feet. The average number of holes bored in the front was 25; at one place, where the rock was less solid, there were only 19 holes. The depth of the holes averaged 1·20 metre, or nearly 4 feet.

From the date of the commencement of operations with Ferroux's machines, to April 30, 1875, a period of nearly twelve months, the depth of the gallery was increased from 897 metres to 2,003 metres, showing an advance of 1,106 metres, or 1,207 yards, equivalent to 10·11 feet per day: a notable acceleration of progress from the substitution of Ferroux's machines.

At this point, the penetration of the great bed of granitic gneiss and the gneiss of Finsteraarhorn was completed.

The enlargement of the tunnel, at the north end, in the segmental upper region, as well as the trenching of the 'strosse,' or core, were at one time wholly executed by machine, for which purpose the perforators of Dubois

and François, Ferroux, Sommeiller (from the Mont Cenis stock), and McKean, have been employed.

Subsequently, the trench only was excavated by machine; and at this work six of Dubois' perforators were employed, drilling the middle and lower portions of the trench, together with one of McKean's vertical drills, which drills the upper portion of the trench. The formation of a shallow trench by McKean's drill is thus effected, in advance of the main trench, reaching to the floor of the tunnel. The enlargement and completion of the excavation was done by hand.

The Dubois perforators were more lately supplemented by four of Ferroux's perforators, making, with McKean's drill, eleven machines at the trench. Adding six machines in the advanced gallery, there was a total of seventeen perforators in actual work.

The advanced gallery at the south end was in loose or inferior rock, cut to a trapezoidal section, with inclined sides, and having a sectional area of 6 square metres. Being close-boarded and strutted, the effective or clear section was reduced to 2 metres, or 6 feet 7 inches, wide at the base, and 1½ metre, or 4 feet 11 inches, at the top, with a height of 2·1 metres, or 6 feet 10½ inches.

In fissured rock, the excavation was made considerably wider, about 10 feet in all; and was about 9 feet 4 inches high; whilst the effective or clear section afforded by the roof-boarding and the strutting was just the same as was left in the portions cut in loose rock. The comparative widening of the excavation afforded a certain clear space on each side for water-spouts from the sides and from the roof, leaving the middle area to that extent free for operations. The struts were cut out of 10-inch trees, and were placed at intervals of about 4 feet from centre to centre.

The excavation of the gallery was performed by hand labour until June 24, 1873, when four, and soon afterwards six, Dubois' mechanical perforators were substituted for hand labour at the front. The total length of gallery accomplished, during a period of 290 days to the end of June, was 219·2 metres, or 239 yards, comprising machine labour for the last six days of June—being at the average rate of 2·47 feet per day.

Dubois' six machines were continually employed at the front, until the end of June 1874, when a total depth of 926 metres, or 1,010 lineal yards, had

been excavated, of which 771 yards had been cut by machine in twelve months, being at the rate of 6·34 feet per day.

The machines of two or more inventors were afterwards placed and worked together on the same carriage at the front—Dubois', McKean's, and Ferroux's; and seven machines were applied at once.

The greater progress made with Dubois' machines at the south end, compared with that at the north end, where it was only equivalent to 2·90 yds. per day, notwithstanding the disadvantages of the frequent and excessive discharges of water, is to be ascribed to the greater facilities presented by the looseness of the soil. At one place, the soil was so friable that it was excavated by hand labour instead of by machine.

The progress at the south end, from the beginning of July 1874, to April 30, 1875, a period of ten months, amounted to 794·5 metres or 867 yards, equivalent to 8·55 feet per day. The total depth penetrated at the later date was 1760·5 metres, or 1,925 yards.

The number of holes mined in the front varied from 7 and 9 to 30 and 31, according to the resisting power of the rock. Towards the end of January 1874, for example, 30 holes were required in a frontage of 67¼ square feet (2½ metres square) of hard rock; whilst, in February, only 7 holes were required, when the miners had arrived at beds of completely disintegrated mica. The ordinary depth of hole bored was 1·2 metre, or nearly 4 feet; and it was often required to charge the holes twice, or even three times, to clear the rock to the bottom of the holes. Experiments were tried with double the depth of hole, 2·4 metres, nearly 8 feet, in depth; but, as they required to be charged four times to clear them out, the ordinary depth of hole was reverted to.

The cutting of the trench has been done by means of McKean's perforators, six being applied with horizontal action to the face of the rock, and four being applied vertically to cut a shallow heading on the top of the core of rock, in advance, making up a total of seventeen perforators in action.

The other portions of the excavation have been performed by hand labour; although it is now arranged to have the whole of the excavation done by machine.

ST. GOTHARD TUNNEL.

Table showing the progress of the Advanced Galleries to April 30, 1875.

Month.	Monthly advance. North end (Goeschenen). Metres.	Yards.	South end (Airolo). Metres.	Yards.	Total. Metres.	Yards.	
	By hand.		By hand.		By hand.		
1872.							
September . .	—		28·7		28·7		
October . .	—		39·4		39·4		
November . .	4·8		17·6		22·4		
December . .	14·1		16·0		30·1		
	18·9	20·7	101·7	111·2	120·6	131·9	In 1872.
1873.							
January . .	21·1		23·8		44·9		
February . .	20·5		18·1		38·6		
March . .	26·7		21·5		48·2		
April . . .	1·5		12·0		13·5		
May . . .	—		22·5		22·5		
June . . .	—		19·6		19·6		
	69·8	76·3	117·5	128·5	187·3	204·8	In 1873.
	By machine.		By machine.		By machine.		
1873.							
April . . .	28·9		—		28·9		
May . . .	42·5		—		42·5		
June . . .	48·1		—		48·1		
July . . .	51·0		47·4		98·4		
August . .	66·6		89·1		155·7		
September . .	50·2		60·2		110·4		
October . .	70·0		60·0		130·0		
November . .	75·0		51·1		126·1		
December . .	79·2		69·0		148·2		
	511·5	559·4	376·8	412·1	888·3	971·5	In 1873.
1874.							
January . .	72·0		51·7		123·7		
February . .	65·8		55·3		121·1		
March . .	82·1		63·2		145·3		
April . . .	58·4		51·9		110·3		
May . . .	82·0		44·8		126·8		
June . . .	70·3		63·1		133·4		
July . . .	95·0		62·0		157·0		
August . .	120·0		59·8		179·8		
September . .	108·2		51·2		159·4		
October . .	113·1		73·4		186·5		
November . .	83·7		84·6		168·3		
December . .	86·5		86·4		172·9		
	1037·1	1133·8	747·4	817·4	1784·5	1951·2	In 1874.

Month.	Monthly advance.					
	North end (Goeschenen).		South end (Airolo).		Total.	
	Metres. By machine.	Yards.	Metres. By machine.	Yards.	Metres. By machine.	Yards.
1875.						
January . .	92·6		101·4		194·0	
February . .	83·1		101·0		184·1	
March . .	92·1		86·7		178·8	
April . . .	97·6		128·0		225·6	
May . . .	115·5		101·0		216·5	
June . . .	99·3		115·0		214·3	
July . . .	113·4		127·2		240·6	
August . .	119·9		95·8		215·7	
September . .	125·9		103·2		229·1	
October . .	127·6		116·2		243·8	
November . .	67·2		90·1		157·3	
December . .	39·3		90·0		129·3	
	1173·5	1283·5	1255·6	1373·2	2429·1	2656·7
1876. January . .	32·5	35·5	121·3	132·6	153·8	168·1
	Totals to January 31, 1876.					
By hand, 1872–73	88·7	97·0	219·2	239·7	307·9	336·7
Machine, 1873–75	2754·6	3012·2	2501·1	2735·3	5255·7	5747·5
Hand and machine	2843·3	3109·2	2720·3	2975·0	5563·6	6084·2

Masonry.—The masonry of the tunnel has been executed in ashlar stone work, varied in detail according to the local requirements of the ground, agreeably to the specified directions and to the details shown in Plates XVIII. and XIX.

STATE OF PROGRESS OF THE WORKS

In the several Departments, on January 31, 1876.

Description of the work.	North end (Goeschenen).		South end (Airolo).		Totals.	
	Metres.	Yards.	Metres.	Yards.	Metres.	Yards.
Advanced gallery excavated	2843·3		2720·3		5563·6	
Enlargement of gallery and widening out of upper part of tunnel	1583·5		1222·0		2805·5	
Trench cut in the core, or lower part of tunnel .	1465·6		902·0		2367·6	
Removal of the remainder of the core . .	818·5		570·0		1388·5	
Excavation completed	88·0		145·0		233·0	
Arch built	797·3		868·7		1666·0	
Wall built, east side	511·0		133·8		644·8	
Wall built, west side	670·0		762·3		1432·3	
Culvert constructed	—	—	126·0	138	126·0	138

GENERAL RATE OF ADVANCE.

The advance made in the heading at each end, during the year 1875, averaged—

For the north end	3·22 metres, or	3·52	yards per day.		
„ south end	3·44 „	„ 3·71	„	„	
	6·66 „	„ 7·23	„	„	

This is at the average rate of three and a third shifts per day of twenty-four hours at each end, allowing one metre of advance for each shift; although, as the actual advance averaged a little more, the actual average number of shifts would be rather less than what is above stated.

The rate of advance is subject to considerable fluctuations, arising from the variable nature of the rock. On April 30, 1875, for example, when the transition took place at the north end from the hard granitic gneiss into the mica-schistous beds, instead of six or seven hours being required to bore 20 holes, 18 holes were bored in three hours, and they were, moreover, blown out to the bottom. The maximum daily advance, for short periods, has been about 5¼ yards at the north end, and 6¼ yards at the south end; total, 11½ yards per day, whilst the total average for 1875 was only 7·23 yards.

At January 31, 1876, it appears that—

The total advance made in the headings was	6,084·2 yards.
The remainder of the headings to be driven was	10,210·8 „
	16,295·0 „

From this it appears that nearly two-thirds of the total length of heading remained to be driven at the above date; and, applying the average rate for the year 1875, say 7¼ yards per day, the remainder will be got through within 4 years, by the end of January 1880, or within 7½ years from the date of M. Favre's contract.

ROCK-BORING MACHINERY.

As at Mont Cenis, the machinery consisted of two parts—the pumps for supplying compressed air, and the perforators or rock-drills worked by the compressed air.

the air before it through the outlet-valves towards the reservoir. As the height of water-column was so adjusted as to drive out the whole of the air, with a portion of water at the same time, there was no clearance or dead space left, and it was easy to calculate the efficiency of the machine. The volume of compressed air made per stroke of the piston was 43 litres, or 1·52 cubic feet, under a pressure of 3 atmospheres. Making 12½ turns, or 50 strokes of the two pistons, per minute, a sufficient quantity of compressed air was obtained to work twelve perforators—that is to say, 2·15 cubic metres, or 77 cubic feet, per minute.

The piston of the compressor having an area of ·159 square metre, or 247 square inches, the useful work done for one stroke was 3,809 kilogrammetres, or 27,550 foot-pounds, as calculated from the indicator-diagram taken from the compressing cylinder.

The area of the steam-piston was ·1963 metre, or 305 square inches, and the indicator-diagram taken from the steam-cylinder showed a total work of 4,534 kilogrammetres, or 32,790 foot-pounds, for one stroke of the piston.

The efficiency of the compressor was therefore $\frac{3{,}809}{4{,}534} = 84$ per cent.

These temporary steam air-compressors were kept regularly at work, at each end of the tunnel, until the beginning of November, 1873, at the north end, and the end of the same month at the south end, after having been at work for more than a year. At these times, respectively, one of the permanent compressors was set regularly to work at each end, and the steam-compressors were placed in reserve.

Permanent Prime-movers and Air-compressors.—As there was a sufficient supply of water-power available in the St. Gothard district, it was decided to employ it, by means of turbines, for working the air-compressing pumps. The two extremities of the tunnel were not equally favoured in respect of water-power. At the south end, the Tessin did not offer a sufficient inclination, and the torrent of the Tremola supplied sometimes less than 300 litres, or 67 gallons, even as little as 200 litres, per second, in the coldest days of winter. It was necessary, in view of such restrictions of the supply, to resort to the excessive height of fall, 181 metres, which was reduced by losses in the conduits

to 165 mètres, or 531 feet, of useful height, at the turbines. So great a vertical height applied to motors of 200 horse-power each, is rare in practice. At the high velocities necessary for working under such a great height of fall, water rapidly attacks wrought or cast iron, and even steel, which become riddled with small holes; and the pieces which receive the shock of the water require to be renewed every four months. Oxidation, accelerated by the compressed air in the water, and by the shock, is probably the chief cause of such deterioration.

At the north end, the torrential bed of the Reuss permitted of securing a fall of 93 metres, or 305 feet. The reservoir of water, for propulsion, was situated at a distance of 796 metres, or 870 yards, above the turbines. The minimum supply from the Reuss was estimated at from 1,200 to 2,000 litres, or from 270 to 444 gallons per second; and the available hydraulic force was more than double that which could be expected at the south end.

With the knowledge of the conditions and extent of the water-supply before him, the contractor decided to employ three turbines at each end, for the reception of the power of the water, and to apply each turbine to drive a distinct group of three air-compressors—in all nine compressors, at each end. Whilst it was anticipated that the supply of air afforded by these means would be sufficient, provision was made for a fourth group of compressors, with a fourth turbine, to be laid down if they should be found necessary. In the middle of 1874 it was, in fact, found to be necessary to augment the power, as the supply of compressed air was scarcely sufficient for the number of perforators in operation, and it was decided to extend the buildings and lay down two more groups of compressors at each end, in order to maintain a full supply of compressed air. These were completed and set to work in the end of 1874, and the beginning of 1875, whilst the provisional steam-compressors had for some months previously been pressed into the service, and continued at work. The benefit derived from these accessions to the compressing power was visible in the accelerated monthly progress made in 1875. It was necessary, of course, to extend the source of water-supply at the south end to supply the additional driving power.

Turbines at Airolo.—The turbines required at the south end were con-

structed by MM. Escher, Wyss & Co., Zurich. They are horizontal, on vertical shafts. The crown of each turbine is of bronze, cast in one piece with its 100 blades. Its exterior diameter is 1·20 metre, or 3·94 feet, and its total thickness is about 11 inches. With plenty of water, the wheel makes 390 turns per minute, when the velocity at the circumference is 24·5 metres or 80 feet per second. The distributor and the directing vanes are in bronze, a metal which in such situations lasts five or six times as long as iron or steel. The shaft of each turbine is fitted with a bevel pinion on its upper end, which gears into a large bevel wheel fixed on a horizontal shaft. This shaft is formed with three throws or cranks, which are coupled to and work the three compressors forming one group.

The turbines are ranged in line, and the horizontal shafts, pertaining each to one turbine respectively, are coupled together end to end, and so united into one continuous shaft. The works done by the several turbines are thus equalised and distributed equally over all the groups of compressors.

Compressors at Airolo.—The compressors were constructed on the system of Professor Colladon by the Société Génévoise de Construction. Alternating with the turbines, the groups of compressors are ranged, and each group of three compressors is driven direct by three cranks on the shaft, one crank to each compressor. The cranks of each group are connected at equal angles round the shaft, and the resistance is thus rendered practically uniform, dispensing therefore with the aid of a flywheel. The motion is uniform, even when the velocity of the turbine is reduced to a half. The three compressors of each group are fixed on one frame-plate, and are placed horizontally. The cylinders are ·46 metre, or 18·1 inches, in diameter; the stroke is limited to ·45 metre, or 17¾ inches, in order that the mean speed of piston may not exceed 1·35 metre per second, or 266 feet per minute, making 90 revolutions per minute—when the turbine makes 390 turns per minute.

The arrangement adopted for coupling the turbines and the compressors to one shaft possesses advantages. When four turbines and five groups of compressors are in working order, they may be connected and be worked together, according to the quantity of water available, or the requirements for perforation. In coupling four turbines to five groups of pumps, a large volume

of air may be compressed to 6 or 7 atmospheres; or the force of four turbines may be concentrated on three groups of pumps to compress the air to 9 atmospheres.

To refrigerate the compressed air within the pumps of the compressors, two means were adopted. In the first place, every piece that is in contact with the air when undergoing compression, is cooled by currents of cold water passed through air-tight envelopes; and the piston-rod is made tubular, and is filled with cold water, which is injected and circulated through the interior of the rod. The circulation is at the same time extended to the interior of the piston.

In the second place, to render the refrigeration still more effective, as well as to lubricate the rubbing surface, cold water in an extremely divided state is injected from the two ends of the cylinder. For this purpose, the water is doubly filtered, so as completely to separate the fine granitic sand which is brought down by the Alpine torrents.

Though the clearance at each end does not exceed 6 millimetres, about $\frac{1}{4}$ inch, there is no liability to shock or concussion within the machine.

The valves for the ingress of air to the cylinder of the pump, and the egress of the compressed air, are inserted in the covers at the ends, and are closed by the action of helical springs. There are no intervening passages on this plan, and the clearance-space is thereby reduced to a minimum: not more than $\frac{1}{4}$ inch of the length of the cylinder at each end. The areas of the openings of the ingress-valves are one-tenth of the area of the piston; and, as the average speed of the piston is not more than 266 feet per minute, the velocity of ingress and egress does not average more than 44 feet per second, a speed which does not induce any sensible withdrawing of the current, or reduction of pressure. The area of the egress-valve is half that of the ingress-valve, and is proportionally more liberal, as an allowance for the passage of the compressed current.

Whilst the clearance spaces, or dead spaces, as they are sometimes called, in the air-pump, are, in these machines, reduced to a minimum, it would be a mistake to assume that they necessarily militate against the efficiency of the machine, for the small quantity of compressed air shut up at the end of the

cylinder, at the termination of each stroke, acts as a spring to aid in propelling the piston towards the other end in making the return-stroke, and so restore the fraction of work done in compressing it. If, then, the clearance were even much more considerable than it is in these machines, or if the compression were pushed to a greater number of atmospheres, and so led to an inferior delivery, the deficiency could be easily made up by running the pump at a greater speed, or by increasing a little the volume of the pump.

The egress-valve at each end of the cylinder, is placed so low as to permit of the simultaneous ejectment of the compressed air and the injected water collected in the cylinder at each stroke.

The volume of water injected is, on this system, reduced to a minimum. It is generally less than one-thousandth part of the volume of the air drawn in. For equal quantities of air inspired, these pumps do not require more than a fourth of the quantity of water which was requisite in working the water-piston of the temporary steam-pump already noticed. The injected water is conducted with the compressed air to the reservoirs; there they are separated.

In making comparisons between the volume and pressure of air compressed into the reservoirs, and those of the air drawn in by the pump, it is necessary to introduce a correction for the diminished atmospheric pressure at such high levels. At the south entrance to the tunnel, the mean barometric pressure is scarcely 66 centimetres of mercury, and it shows that the weight of air in a given volume is only 87 per cent. of that of air under one atmosphere of 76 centimetres. There is, therefore, a proportional reduction of the volume of air of a given density of compression, produced by a given number of strokes of the pump, as compared with the volume produced from air of the normal atmospheric pressure.

Reservoirs for Compressed Air at Airolo.—The compressed air and water, discharged from the compressors, are delivered into a system of four reservoirs, connected successively with each other by pipes, in such a manner that the air and water are, in the first place, collected from the several groups of compressors in a main pipe, by which they are conducted and delivered into the first reservoir at one end, where the water is separated from the air. The air

then passes from the other end of the first reservoir, by a pipe, into the near end of the second; and similarly from the second to the third, and from the third to the fourth reservoir. In this way, the reservoirs act as equalisers, to reduce to uniformity the waves of pressure from the compressors. They consist of wrought-iron cylinders, with hemispherical ends, 1·62 metre, or 5·3 feet, in diameter, and 9 metres, or 29½ feet, long, having each a capacity of 16·8 cubic metres, or 593 cubic feet.

DIMENSIONS OF THE TURBINES AND COMPRESSORS AT AIROLO.

Diameter of main supply pipe	·62 metre,	or 2·03 feet.
Diameter of the turbines	1·20 „	„ 3·94 „
Diameter of the pinion on the vertical shaft	·70 „	„ 2·3 „
Number of teeth	35	
Diameter of the large-toothed wheel	3·04 metres,	or 10·0 feet.
Number of the teeth (wood)	152	
Number designed for another wheel for compressing to 9 atmospheres	180	
Diameter of cylinder of compressors	·46 metre,	or 18·1 inches.
Diameter of the piston-rod	·10 „	„ 3·9 „
Stroke of the piston	·45 „	„ 17·75 „
	Per second.	Per minute.
Mean speed of the piston	1·35 metre,	or 266 feet.
Distance from centre to centre of cylinders	·75 „	2·46 „
	Cubic metres.	Cubic feet.
Capacity of an air-reservoir	16·80	or 593
Capacity with the conduit up to the valve	17·26	„ 609

ELEMENTS OF THE WORK OF THE COMPRESSORS AT AIROLO.

Height of useful fall of water	165 metres, or 531 feet.
Quantity of water delivered per second, when there is a good supply, for one turbine	160 litres, or 35½ gallons.
Maximum useful effect guaranteed for one turbine, at the vertical shaft	210 horse-power.
Do., do., at the horizontal shaft of the compressors	200 horse-power.
Quantity of air of atmospheric pressure at Airolo drawn in per stroke, without making allowances	71 litres, or 2·5 cubic feet.
For 85 turns per minute, or 510 strokes of three cylinders or one group, there are drawn in, without making allowances	36.210 „ „ 1,278 „
With four groups there may be drawn in, per minute	144,840 „ „ 5,112 „

ELEMENTS OF THE WORK OF THE COMPRESSORS AT AIROLO—(*continued*).

	Cubic metres.		Cubic feet.
Do., do., 24 hours	208,568	or	7,363,000
The production required from 4 groups in 24 hours	140,000	„	4,941,000
Reduced volume, compressed to 8 atmospheres .	17,500	„	617,625

Goeschenen.—The general arrangement of the prime-movers and compressors at Goeschenen is similar to that of the machinery at Airolo, though the machines differ to some extent in detail. The whole of the machinery was constructed by MM. B. Roy & Co., Vevey.

Turbines at Goeschenen.—Three turbines were erected on the system of Girard—a system which possesses the advantage of being capable of working either horizontally or vertically, when the water is received only on one portion of the circumference. The choice of the system was made by the constructors, who, after having had experience of many other systems of turbine, finally adopted the Girard turbine, which, in their opinion, admitted of utilising, with the best effect, variable quantities of water.

Near each of the three groups of compressors which were, in the first instance, constructed, is placed a Girard turbine, with a horizontal shaft, or 'wheel-turbine,' from which the power is transmitted to the compressor-shaft, which is parallel to it, by means of two pairs of spur-wheels, in the ratio of 1 to 2, one pair of wheels being fixed on the turbine-shaft, and the other pair on the compressor-shaft, one wheel at each extremity of this shaft.

These three turbines, calculated for an effective fall of 85 metres, or 279 feet, and a maximum charge of water of 300 litres, or 66·6 gallons, per second, correspond to an effective power of 250 horses each. The regular speed is 160 turns per minute. Their external diameter is 2·4 metres, or 7 feet 10½ inches, and they have 80 buckets. The distributor contains 8 orifices; and, with 9 orifices, augmenting the supply of water in the ratio of 8 to 9, the power, when needed, may be increased to 280 horse-power—a power for which the turbines are constructed, in case it may occasionally be required to elevate the pressure to 10 atmospheres.

The main supply pipe conducts the water to within 150 metres from the turbine-house. It is ·85 metre, or 2·79 feet, in diameter, and is 650 metres, or 709 yards, in length. It is constructed of sheet-iron, riveted together in

lengths of 6 metres, or 19·7 feet, united by flanges with india-rubber joints; it is 5 millimetres in thickness at the upper part, and the thickness is increased to 6, and finally to 7 millimetres at the lowest part:—that is, ·20, ·24, and ·28 inch, thickness. The main pipe is branched into two small pipes of cast-iron, with flange-joints, ·62 metre, or 2·03 feet, in diameter, in lengths of 3 metres, or 9·84 feet. Each of these branches is proportioned for the supply of water to two turbines.

Compressors at Goeschenen.—Three groups of compressors were at first erected at Goeschenen. The production required from each group of compressors was 4 cubic metres, or 141 cubic feet, of compressed air, at 7 atmospheres effective, or 8 atmospheres absolute pressure, per minute, and capable of being delivered occasionally at 10 atmospheres absolute, for which the volume would be proportionally less. To effect this rate of delivery, as the speed of the turbine was to be 160 turns per minute, that of the compressor-shaft would be 80 turns per minute; the diameter of cylinders was fixed at ·42 metre, or 16·5 inches, and the stroke at ·65 metre, or 25·6 inches. The maximum volume of air drawn in per stroke is 87·55 litres, and per double stroke 175·10 litres, and per minute 14,008 litres; or, for the three compressors in one group, 42,024 litres, or 1,483 cubic feet per minute. Whence—

Maximum volume of air of atmospheric pressure, drawn in per minute, by one group of compressors	1,483	cubic feet.
Do., do., four groups of compressors	5,732	"
Do., do., in 24 hours	8,254,080	"
Required volume of atmospheric air drawn in, in 24 hours, making ample allowance for want of perfect efficiency	6,349,000	"
Reduced volume, when compressed to 8 atmospheres	793,625	"

The piston of the compressor and its rod are hollow, and are cooled by cold water circulated within them, on Colladon's principle, as in the compressors at Airolo. But at Goeschenen, in addition, the circulation of cold water is applied also to the periphery of the piston, externally, and so the water is brought into direct contact with the cylinder, and cools it. The piston is 7 inches deep, and is packed with two gun-metal rings, one near each face. The intermediate space between the rings is turned down, and so receives a thin stratum of cold water, which enters from the interior of the piston,

through a hole formed in the upper part. This water is maintained under a pressure greater than that of the air compressed within the cylinder, and therefore forms an air-tight packing round the piston, at the same time constantly cooling the walls of the cylinder, by which it is enclosed. A certain proportion of the water also passes by the piston into the cylinder, and cools the air whilst undergoing compression—thus augmenting the quantity of compressed air produced, in preventing its dilatation by heat.

The pressure under which the water is introduced into the piston is that due to the fall of 93 metres, or 305 feet, under which the water is brought for working the turbines. The absolute pressure due to the fall is about 9 atmospheres, and to increase the pressure when required, a pump is provided, worked off the pinion-shaft, making 26 turns per minute, capable of delivering, under increased pressure, 2 litres, or ·44 gallon, of cold water per minute. The water for the supply of the pistons is thoroughly purified by being passed, under pressure, of course, through a filtering reservoir, containing three diaphragms of perforated sheet-iron, whence it is conducted direct to the piston or to the forcing-pump.

The air is drawn into the compression-cylinder through two inlet-valves in the upper part of each cover, and is discharged, together with the water collected in the cylinder, through three other valves, of less diameter, placed in the lower part of the cover, into a small receiver at one end of the cylinder. A float in the receiver, in connection with a cock, forms a self-acting arrangement for letting off a portion of the water collected in the receiver, from time to time, so preventing the water from rising to an inconvenient level. The compressed air is conducted from the upper part of the receiver into large reservoirs.

DIMENSIONS OF THE TURBINES AND COMPRESSORS AT GOESCHENEN.

Diameter of main supply pipe	·85 metres, or	2·79 feet.
Diameter of the turbines	2·4 „ „	7·87 „
Diameter of the small wheels on the turbine-shaft	1·4 „ „	4·6 „
Diameter of the wheels on the compressor-shaft	2·8 „ „	9·2 „
Diameter of cylinders of compressors	·42 „ „	16·5 inches.
Diameter of the piston-rod	·07 „ „	2·75 „
Stroke of the piston	·65 „ „	25·6 „
Mean speed of the piston, per second	1·85 „ „	6·07 feet.
Distance from centre to centre of cylinders	·75 „ „	2·46 „

TOTAL QUANTITY OF AIR PROVIDED FOR,

To be delivered into the St. Gothard Tunnel in the course of 24 hours.

	At atmospheric pressure.	At 8 atmospheres.
At the south end	4,941,000 cubic feet.	617,625 cubic feet.
At the north end	6,349,000 „	793,625 „
Total in 24 hours . . .	11,290,000 „	1,411,250 „

CONDUITS FOR COMPRESSED AIR.

The compressed air is conducted into the tunnel by a tube about 8 inches in diameter (20 centimetres); it is diminished to 4 inches, and finally to 2·4 inches in diameter at the front (10 and 6 centimetres). The actual effective pressure near the reservoirs is from 6 to 7 atmospheres; and at the front from 3½ to 4 atmospheres. The pressure at the front should not be lower than 4 atmospheres.

PERFORATORS OR ROCK-DRILLS.

Dubois and François' Rock-drill.—The first machine used for boring the rock in the advanced galleries was the perforator of MM. Dubois and François, of Seraing. This perforator is extensively employed in the Belgian collieries in the blasting of rock and shale. It is based on the principle of M. Sommeiller's drill, which was used in the excavation of the Mont Cenis Tunnel, but it is much simpler in construction and detail than Sommeiller's. The successive movements in this, as in most other rock drills, are:—

1. To deliver quickly, and in rapid succession, the blows of a jumper on the rock.

2. To turn the jumper on its axis, after the blow is delivered, not only to increase the effect of the next blow, but also to prevent the drill from getting fast in the rock.

3. To advance the drill, at the will of the miner, so as to regulate the length of the stroke of the drill, and to follow up the work as the hole is deepened.

4. To withdraw the machine promptly when the tool or the machine itself is to be changed.

The principal dimensions of the perforator are :—

Diameter of the percussion-cylinder . .	7	centimetres,	or 2·76	inches.
Diameter of the percussion piston-rod . .	5	„	„ 1·97	„
Length of stroke	2 to 18	„	or $\frac{3}{4}$ to 7·2	„
Total length of the machine	2·20	„	or 7·2	feet.
Width „ „	·23	„	„ 9·2	inches.
Height „ „ at the middle .	·32	„	„ 12·6	„
Weight of the percussion-piston, with its rod	28	kilogrammes,	or 62	lbs.
Total weight of the machine . . .	220	„	„ 485	„
			or $4\frac{1}{3}$	cwt.

The boring-bars, which are keyed to the piston-rod of the machine, are of steel, octagonal in section, and 25 millimetres, or 1 inch, in diameter over the angles. They are of considerable length. In very hard sandstones, they work well at a length of 1·25 metres, or 4 feet; in soils of medium hardness, at a length of 1·5 metre, or 5 feet; and from 1·8 to 2 metres, or from 6 to $6\frac{1}{2}$ feet, in easy rocks. They bore holes of 35 centimetres, or 1·4 inches, in diameter. The cutting edge is, for collieries, in the form of the letter Z, or of a cross; for the work of the St. Gothard Tunnel a simple chisel edge is used.

The capacity of the cylinder is 1·3 litre, or 79·3 cubic inches; the maximum quantity of air consumed per stroke is 97·6 cubic inches.

Perforator-carriage.—The carriage designed by MM. Dubois and François, and employed at St. Gothard, was fitted to receive six perforators. Its weight was about 5,000 kilogrammes, or nearly 5 tons. It possesses the following qualifications :—

1. The perforator might be set in any position for working.

2. The carriage was fixed independently of external lateral support, and the miner could move freely about the machine. It was difficult, besides, to find lateral support in many circumstances; in hard rocks it was impossible.

3. The perforators were solidly fixed, and enabled to withstand the reaction from the force of impulsion upon the piston.

4. The perforators could be made of such dimensions that holes $2\frac{1}{2}$ feet

deep could be bored without changing the boring-bar; or even, if needed, holes of a depth of 5 feet or 6½ feet.

The carriage was placed on four wheels, on a line of rails. The frame was constructed of cast and wrought iron, bolted and riveted together. It was about 10 feet long, and stood nearly 4 feet high, above the rails. The perforators were double-jointed to the frame near the rear end, with horizontal and vertical movements, and could be pointed towards any part of the front, as required. An additional means of adjustment was afforded by vertical screws in front and behind; and, by the combined use of these appliances, each perforator could be set with promptitude and facility. It was of prime importance that the perforators should be immovably fixed in the direction in which the holes were bored, for on this condition depended the economical use of the rock-borer. The stability of the carriage during the attack was secured by blocking it up off the rails, on fir-battens. This was the best plan; strutting off the walls of the gallery did not answer.

The means of advancing the percussion-cylinder at will offers the advantage of enabling the miner easily to shorten or lengthen the stroke of the piston, the length of which ranges from 2 to 18 centimetres, or from ¾ inch to 7·2 inches, whether it be necessary to strike with short strokes in the preparation of an attack, or to strike with full force the front of an ordinary rock. In perforating rocks of great hardness, such as quartzites, the drills may be spared by striking more rapidly and less violently—an alternative which is often of great service for securing regularity of operations, whilst it does not much reduce the efficiency of the perforator. The ordinary number of blows given by the Dubois and François perforator is from 250 to 300 per minute; very short strokes may be delivered at the rate of 500 per minute.

According to the greater or less pressure of the compressed air used, the horse-power to work one machine may vary from 3 to 5 horse-power.

The rate of boring in sandstones, according to experience in Belgium, is 1·6 inch per minute; in slate, from 6 to 8 inches per minute. In calcareous rocks, it is estimated at twenty times the rate of advance by hand.

Ferroux's Rock-drill.—This perforator, like Dubois', operates by the pressure of compressed air on a piston and its rod, to which the boring-bar is

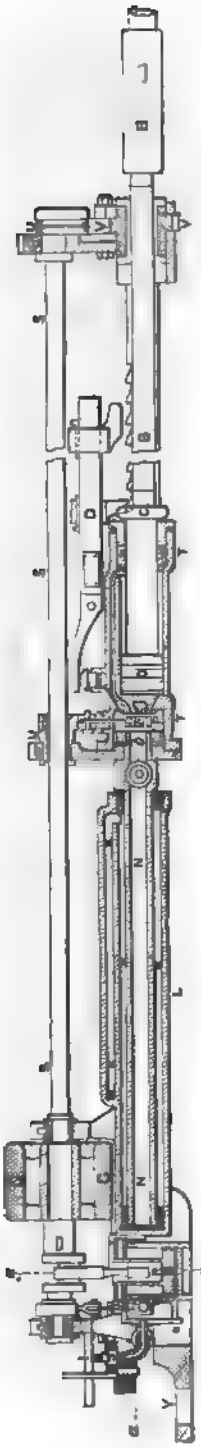
attached. It contains, in addition, an automatic movement, by which the percussion-cylinder is advanced spontaneously and follows up the hole that is bored. In Dubois' machine, the advance of the machine was conducted by hand, and for want of exactness in the manipulation, frequent damage was occasioned to the cylinder by knocks and wrenches—a species of accident which rarely happened to Ferroux's machine.

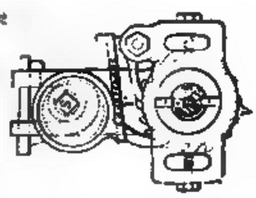
The automatic movement in Ferroux's machine consists of an air-cylinder fixed behind and on the centre line of the percussion-cylinder, having a piston and rod which are connected to the head of the percussion-cylinder. The piston of this, the propelling cylinder, is constantly under the pressure of compressed air, by the agency of which the percussion-cylinder is moved forward when freed to be moved, and is kept taut to its bearings in front when at rest. These bearings consist of a pair of ratchets, the forks of which are engaged in the teeth of two racks, one on each side of the machine. The teeth of these racks are placed at 3 centimetres, or 1·2 inch pitch, and they measure the successive steps of the advance of the percussion-cylinder. When it becomes necessary to advance this cylinder, the ratchets are raised clear of the racks, and the cylinder is instantly moved forward by the force of the air on the piston of the propelling cylinder behind it. The ratchets fall into the next notches of the racks, and are there set fast by the propelling pressure until they are again lifted for the next advance. The raising of the ratchets at the right time, is effected by a collar on the percussion piston-rod, which strikes a tappet in connection with them, and raises them just as the stroke of the drill reaches its appointed maximum length.

The percussion-cylinder is secured behind, by means of another pair of ratchets, which engage in two other racks on the frame, the teeth of which are directed the other way. The ratchets are set fast in the racks by the pressure of compressed air.

By these means the percussion-cylinder is maintained perfectly steady whilst in action.

The percussion-cylinder, it may be added, receives its supply of compressed air from the propelling cylinder, from which it passes through its piston-rod, which is tubular, into the valve-chest of the percussion-cylinder.





FERROUX'S ROCK-DRILL

B, the boring-rod, fixed to O, the piston of the percussion cylinder T T, on the rod of which the collar C is formed, for lifting the ratchets for the feed, by striking a tappet on the forked lever D, carrying the ratchets. P, the valve-chest, and Q, the slide valve for supplying and distributing air to the V percussion cylinders, driven by an eccentric U on the longitudinal slotted shaft S. The air is supplied through the hollow rod N N, fixed to the piston M, in the propelling-cylinder L, for which K K is the air-passage. Air is admitted to the annular space K K round the piston-rod, for withdrawing the percussion-cylinder. R is the cylinder with piston for turning the longitudinal shaft S, having a fly-wheel G; on the shaft are fixed the eccentrics U, U, the first of which moves the slide-valve of the percussion-cylinder, and the second moves the revolving ratchet-feed V on the boring bar. By the socket Y the drill is fixed to the supporting frame.

The slide-valve, for distributing the air to the percussion-cylinder, is moved by an eccentric on a longitudinal traversing shaft, which passes over the whole length of the machine. This shaft is turned by means of a short vertical cylinder at the head of the machine, 9 centimetres, or 3·6 inches, in diameter, with a stroke of 7 centimetres, or 2·8 inches. The speed at which this shaft revolves regulates the rapidity of the strokes of the drill. At the same time, the independence of the movements of the valve with respect to those of the piston, gives rise to frequent false strokes, which cause a waste of air.

At the extreme end of the machine, this shaft carries an eccentric, which, by means of a ratchet, turns a ratchet-wheel on the percussion-rod a definite fraction of a turn for each stroke, and thus the revolving movement of the drill is effected.

To withdraw the percussion-cylinder and its appendages from the front, when the boring of the hole is completed, or for any other reason, the pressure of the compressed air is reversed on the propelling piston, and the cylinder is instantly withdrawn.

Sectional views of Ferroux's rock-drill are here annexed, with literal references.

The principal dimensions of the rock-drill are:—

Diameter of the percussion-cylinder . .	8·4 centimetres, or	3·36 inches.
Diameter of the percussion piston-rod . .	7 „ „	2·8 „
Maximum length of stroke	16 „ „	6·4 „
Diameter of the propelling cylinder . . .	8 „ „	3·2 „
Diameter of the piston-rod	5 „ „	2·0 „
Travel of the propelling piston . . .	75 „ „	30 „
Total length of the machine	3·30 metres „	10·8 feet.
Width „ „	26 centimetres „	10·4 inches.
Height „ „	36 „ „	14·4 „
Weight „ „	260 kilogrammes „	572 lbs.
„ (recently improved)	180 „ „	396 „

The capacity of the percussion-cylinder of Ferroux's machine is 1·7 litre, or 104 cubic inches; and 2·3 litres, or 140 cubic inches, of compressed air are consumed for one stroke. When regularly at work, the machine has made from 250 to 300 strokes per minute. But, by simplifications of the machine, more recently effected, it has made, with 6 atmospheres of pressure, and a jumper 35 millimetres, or 1·40 inch, in diameter, according to the results of trials, 450 strokes per minute, and bored a hole, about 2½ inches in depth, in the hard granitic gneiss.

McKean's Rock-drill.—This drill was at work in the tunnel at an early date, but in the course of the year 1875 considerable improvements were made in it. The body of the McKean drill is cast of phosphor-bronze. The air-cylinder is 4 inches in diameter; the piston is of wrought iron, 2 inches thick, fitted with two pairs of Ramsbottom's rings. The piston-rod is 2¼ inches in diameter, and is screwed and pinned into the piston. The maximum stroke of the piston is 5 inches, the minimum stroke is 2 inches, and the average length of stroke when at regular work is 3½ inches. The machine can bore to a depth of 3 feet at one setting. The drill is, of course, worked by compressed air, and it is calculated that 62 cubic inches of air are used for a stroke of 4 inches. The drill can be moved with less than an atmosphere of pressure, and it is capable of making from 500 to 700 strokes per minute, with air of 5½ atmospheres of effective pressure. The total weight of the machine is 506 pounds. It is 7 feet 6 inches long and 10 inches

by 9 inches in width and depth, extreme dimensions. At the comparative trials above referred to, the drill penetrated, whilst actually at work, from 3 to 8 inches per minute, and made 800 strokes. With 6½ atmospheres of pressure, it has penetrated as much as 12 inches in a minute.

The turning movement of the drill is effected by means of a cylindrical enlargement formed on the piston-rod. Helical grooves are cut on the face of this enlargement, which is constantly in gear with a helically grooved cylinder placed parallel to the piston-rod, and capable of revolving. On the return-stroke of the piston, the cylinder is maintained by a ratchet-motion in a fixed position, whilst the piston-rod, sliding upwards in gear with the cylinder, is necessarily turned on its axis to a degree proportionate to the twist of the spiral and the length of the return-stroke; thus the new angular position of the jumper is secured. During the forward stroke, the spiral cylinder does not influence the piston-rod, which moves straight forward, and, on the contrary, turns the cylinder on its own axis. Nevertheless, as a precaution, the piston-rod is prevented, by a ratchet-motion, from returning to its previous angular position in making the forward stroke. On the next back-stroke, the piston-rod is again seized by the spiral cylinder, which is now brought up against its ratchet-detent, and it is turned round, as before, preparatory to making the next forward stroke.

The compressed air is supplied to and exhausted from the cylinder through a hollow cylindrical valve, formed with suitable openings. For this purpose, the valve receives an oscillatory movement on its axis, by means of tappets fixed on its spindle, which are moved alternately to the right and to the left, on the forward and backward strokes respectively, by the enlargement on the piston-rod. The ends of the enlargement are formed conically, in order to move the tappets steadily and fairly.

The action of the enlargement on the tappets is also utilised for effecting the feed or advance of the jumper. The reciprocations of the backward tappet are communicated to a lever fixed to one of a pair of crown ratchet-wheels, placed together on the feed screw, and held in gear with one another, like clutches, by a helical spring. The first of these, the lever-wheel, reciprocating in unison with the tappet, is loose on the spindle, but the second is

feathered, and engages in a longitudinal groove cut in the spindle. Thus, as the second wheel is turned, it turns the spindle with it, which, by the screw, advances the cylinder. The teeth of the first wheel slide over those of the second wheel, in one direction, and engage them in the opposite direction. When, therefore, in the ordinary course of reciprocation, the first wheel is pushed round far enough by the tappet-movement, it advances its hold upon the second wheel, by the interval, usually, of one tooth at a time, and, when withdrawn, it pulls round the second wheel and the screw with it, which gives the feed. Should the first wheel not be pushed round far enough by the tappet-movement, to gain a tooth, the teeth of the first wheel slip back into the same places, and no advance is made. But the play of the tappet is increased as the stroke increases with the penetration, in virtue of the conical form of the surface of the enlargement; so that finally, when the length of the stroke has reached the maximum designed for it, the first wheel is advanced far enough to gain a tooth upon the second, turns it, and gives the feed. As there are fifteen teeth in each ratchet-wheel, each advance of one tooth is equal to a fifteenth of a revolution, and the pitch of the screw, formed with a double-thread, is 1 inch; consequently, each advance of the feed by one tooth is just $\frac{1}{15}$ inch. By this simple combination of the double ratchet-wheel and the screw, the feed is thus minutely graduated, and the stroke of the piston, on regular work, becomes practically constant.

Figs. 1 and 2 are views of the McKean rock-drill in plan and elevation; fig. 3 is a cross section through the valve; and fig. 4 a section at the conical enlargement of the piston-rod, showing the motion for the screw-feed. The principal dimensions are as follow :—

Diameter of the cylinder	4 inches.
Diameter of the piston-rod	$2\frac{1}{4}$ „
Length of stroke	2 to 5 „
Average length of stroke, regular working	$3\frac{1}{2}$ „
Travel of the machine	36 „
Total length of the machine	7·5 feet.
Width „ „	10 inches.
Height „ „	9 „
Weight „ „	506 lbs.

The drill-carriage, or *affût*, for the McKean rock-drill is illustrated by

figs. 5 and 6 (p. 314), the frame mounted with drills being shown perspectively in fig. 5, and the frame in plan in fig. 6. It is constructed of wrought-iron bars, 5 inches wide by $1\frac{1}{4}$ inch thick. It is 12 feet in length, and 4 feet 6 inches high, and is placed on four 16-inch wheels, which run on the line of rails leading to the front. The frame is 2 feet 8 inches wide at the back, and is only 2 feet wide at the fore-part, being 8 inches narrower at the front than at the back, in order that the machines, which are placed upon it, may be ranged inwards, when required, towards the centre

FIG. 3.

FIG. 4.

of the front. The drill-frame shown in the figures is constructed to mount four rock-drills. The back end of each machine is carried on a 3-inch horizontal pivot, on which it may be elevated or depressed to any angle. The pivot may be raised or lowered by means of a vertical screw; so likewise may the fore-end of the machine. Similarly, the two ends of each machine are controlled by horizontal screws. There are thus four screws for the adjustment to position of each machine, and any one machine may be ranged over the whole surface of half the fore-head on the same side as that at which the machine is placed. There is a cylindrical distributor of compressed air fixed at the back of the frame, 10 inches in diameter, and 4 feet

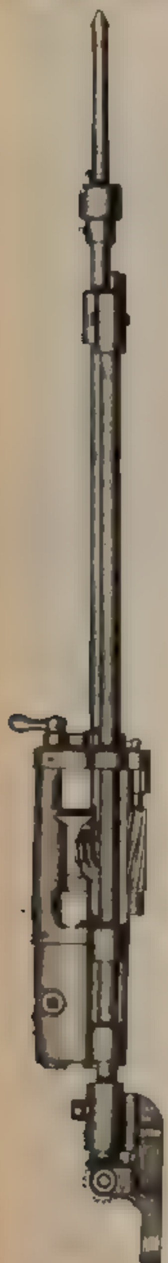


FIG. 1.

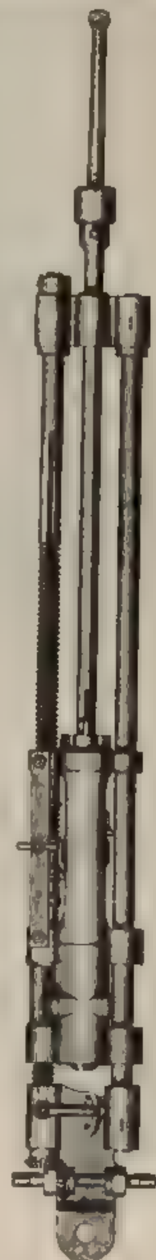


FIG. 2.

long, made of $\frac{3}{8}$-inch iron plate, welded at the seam. India-rubber hoses, 1 inch in diameter, are attached to the distributor, and conduct the air to each machine.

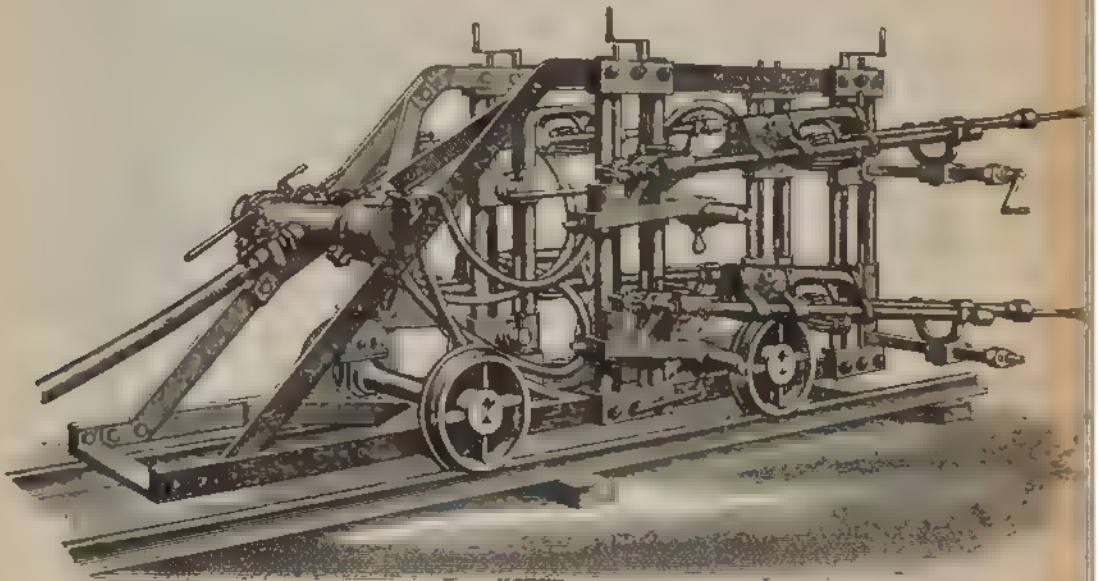


Fig. 5.

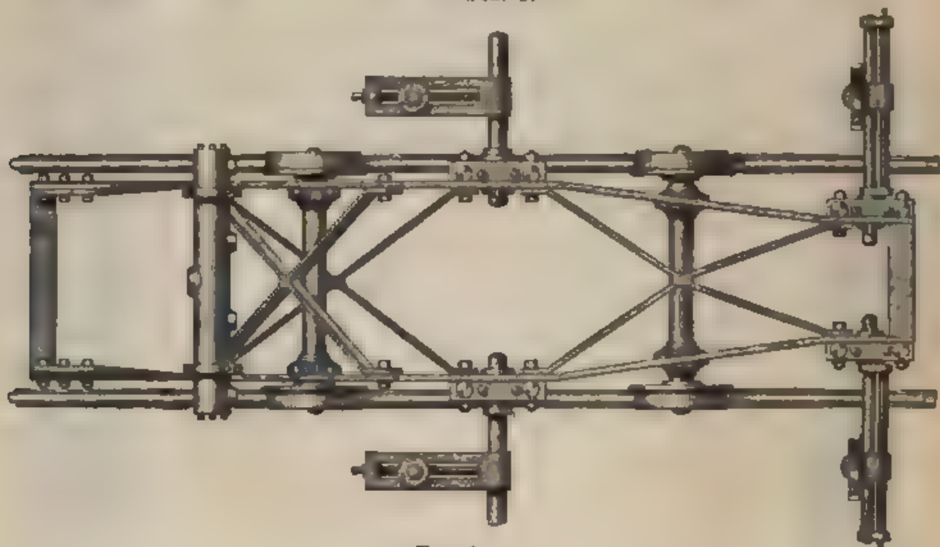


Fig. 6.

In drill frames constructed to carry six machines, the sides of the frame are made parallel throughout, and the two additional machines are mounted on the inside, between the sides.

The following are the leading particulars of the three most prominent rock-drills that have operated in the St. Gothard Tunnel:—

Rock-drill.	Diameter of cylinder.	Stroke.	Air consumed per stroke.	Weight.	Dimensions.
	Inches.	Inches.	Cub. ins.	Cwt.	Ft. Ins. Ins.
Dubois . . .	2·76	·75 to 7·2	97·6	4·33	7·2 × 9·2 × 12·6
Ferroux, improved .	3·36	max., 6·4	140·0	3·54	10·8 × 10·4 × 14·4
McKean, improved .	4·00	2 to 5	62·0	4·52	7·5 × 10 × 9

ARRANGEMENT OF THE WORK OF EXCAVATION.

It is intended to perform the work of perforation entirely by machine, dispensing, if possible, with hand labour. It is not, in fact, possible to dispense entirely with hand labour for excavating soft, friable rock; it has been found better to substitute hand labour for machines. Nevertheless, in ordinary hard rock, the machines are employed exclusively. The sectional area of the tunnel is divided into seven sections: three on the upper level—the level of the floor of the heading; and four on the lower level—that of the floor of the tunnel.

The culvert constitutes an eighth, and smaller section. Each of these sections, separately, is attached by a group of drills, as follows:—

	Number of drills
The heading, or *avancement*	6 to 9
The right wing of the heading, widening out, or *abattage* . . .	3 to 5
The left „ „ „ „ . . .	3 to 5
The shallow trench, with core, or *petite cunette*	2
The deepening of the trench to the floor of the tunnel, or *grande cunette* .	6 to 9
The greater mass of the core, to the right of the trench, or the *strosse* .	6 to 9
The narrower mass of the core, to the left of the tunnel, or the *piedroit* .	3
The culvert, or *canal*	1
Total number of rock-drills at each end	24 to 43

The faces of the several sections are, of course, at various distances from the front, at intervals of from 50 to 150 metres (55 to 164 yards), one behind another. By such disposition, the operations on one section are not interfered

with by those on the others. From the face of the heading to the face of the excavation for the culvert—the last in succession—the interval may amount to 1,000 metres (1,090 yards).

COMPARATIVE PERFORMANCE OF MECHANICAL PERFORATORS AT ST. GOTHARD TUNNEL.

In boring holes 35 centimetres, or 1·4 inch, in diameter, in the granitic gneiss at the north end of the tunnel, with an effective pressure of 5½ atmospheres, the following were the depths per minute bored by the perforators of different constructors, according to the official report of the results of trials made early in 1874 :—

	Centimetres.		Inches.
Ferroux (early machines)	4·01	or	1·60
MacKean " "	3·50	"	1·40
Dubois and François	2·60	"	1·04
Sommeiller	2·12	"	·85

Other comparative observations were made in July—September 1874, on the general performances of Dubois and François' machines and Ferroux's machines, at regular work. It was officially reported that six machines of each kind worked at the granitic gneiss at the north end—Ferroux's being stationed in the advanced gallery, and the others in the trench. A total length of 100 metres of holes was bored by each of the two groups of six machines, with the following results :—

To Bore 100 metres of holes by Six Machines of each Maker.

		Dubois and François.	Ferroux.
Total time in boring, and in changing the drills and the machines when worn or disabled—	hours . .	24·3	15·9
Total length per minute with six machines	centimetres	6·86	10·5
	or inches .	2·74	4·2
Total length per minute for each machine	centimetres	1·14	1·75
	or inches .	·46	·70
Number of fresh drills used		668	621
Number of machines disabled and removed for repair .		6·3	3·5

It is stated, with respect to these trials, that the pressure of the air supplied to Ferroux's machines was 1 atmosphere less than that of the air supplied to Dubois and François' machines.

It is evident, on comparing these net advances by one machine with the actual advance whilst in action, that much time was lost in renewing the drills and the machines. Thus—

	Inches per minute. Dubois and François.	Ferroux.
When actually boring, the advance was at the rate of . .	1·04	1·60
The net advance was at the rate of	·46	·70

Showing that the net advance, in each case, was 44 per cent. of the advance whilst actually boring, and that more than half the time was lost in replacing the worn drills and disabled machines.

This point, of the durability and permanence of the perforators, requires, in fact, the most urgent attention of constructors. It is obvious that the machines lose half their efficiency for want of endurance. The superiority of Ferroux's machines in this respect to Dubois and François', is mainly owing to a greater solidity of construction, which renders the repairs less frequent and the interruptions fewer, notwithstanding that it consists of a greater number of pieces; and also to its perfect automatic action for advancing the percussion-cylinder, before referred to.

After all, the breakages which occur most frequently in Ferroux's, as well as in Dubois and François' machines, are the fractures of the piston-rod by reason of the repeated shocks to which the rod is submitted, by concussion. The iron of which it is constructed, it has been observed, appears to be gradually transformed from a fibrous material into a crystalline and brittle material.

From other observations made and officially reported in the beginning of 1875, the following were found to be the lengths of time required by one of each system of perforator, to bore a hole 1 metre in depth. In these times, all the delays occasioned by the changing of jumpers, machines, &c., are

averaged and included—delays which are unavoidably incurred in work of long duration :—

	Total length driven.	Machines.	Time to bore 1 metre by one machine.
Advanced gallery, north end .	6,352 metres.	Ferroux (early).	1 hour 9 minutes.
Do. do. .	4,226 „	Dubois.	1 „ 31 „
Advanced gallery, south end .	2,617 „	Do.	1 „ 24 „
Widening do. do. .	623 „	Sommeiller.	2 „ 54 „
Trench do. .	205 „	McKean (early).	2 „ 1 „

It is added that the cost for repairs of the perforators working at the north end, during the three months, October—December 1874, was, per metre of holes bored, as follows :—

	s.	*d.*	
Ferroux's perforator, 2·43 francs per metre, or	1	9	per yard.
Dubois' do. 4·27 „ „ „	3	1	„

The general results of the mechanical perforation of the tunnel, during the year ending September 30, 1874, are given in the annexed tables, for the north end and the south end respectively. Recalling what has been previously stated, in general explanation of these tables, it may be remarked that the large numbers of machines disabled, shown in the second last lines of the tables, demonstrate that the machines which worked at the front—those of Ferroux, and Dubois and François, were miserably deficient in endurance. At the south end, working in comparatively friable rock, the machines of Dubois and François were disabled at the rate of about one per attack or shift, all round the year; whilst at the north end, working in the granitic gneiss, which was harder than the rock at the south end, Ferroux's machines were disabled at the rate of $1\frac{5}{8}$ machines per shift.

ST. GOTHARD TUNNEL—NORTH END.

Results of Mechanical Perforation in the Advanced Gallery, during the Year ending September 30, 1874. Material—Granitic Gneiss.

ELEMENTS FOR COMPARISON. (Dubois and François' machines were used to May 8, and succeeded by Ferroux's.)	During the Three Months ending				For the year ending Sept. 30, 1874.
	Dec. 31, 1873.	March 31, 1874.	June 30, 1874.	Sept. 30, 1874.	
Number of days	92	86[1]	91	92	361
	Metres.	Metres.	Metres.	Metres.	Metres.
Quarterly advance	224·25	214·45	210·70	323·20	972·60
Average daily advance	2·49	2·49	2·31	3·51	2·69
Maximum daily advance	4·20	4·60	3·90	6·00	6·00
Advance per attack or shift	0·94	0·91	0·89	1·07	0·96
Total number of attacks	237	235	236	302	1,010
Number of attacks per day	2·63	2·73	2·59	3·28	2·80
	h. m.	h. m.	h. m.	h. m.	h. m.
Average time to drill per attack	4.46	5.0	5.15	3.54	4.44
,, ,, to blast and clear away	4.20	3.46	3.24	3.18	3.42
,, ,, from one attack to the next	9.5	8.46	8.39[2]	7.12	8.26
Total number of holes bored	5,659	5,622	5,757	6,387	23,425
Average number per attack	23·9	23·9	24·4	21·2	23·2
	Metres.	Metres.	Metres.	Metres.	Metres.
Total length of all the holes	5,906·4	5,787·0	5,809·0	7,542·0	25,044·4
Average total length per attack	24·8	24·6	24·6	25·0	24·8
,, ,, of a hole or an attack	1·04	1·03	1·01	1·18	1·07
Length of all the attacks	246·5	242·0	238·0	356·4	1,080·7
Number of machines sent for repair	545	548	307	266	1,666
,, ,, per attack	2·29	2·33	1·30	0·88	1·65

[1] Four days of experimental trials are excluded. [2] Not including 113 hours' stoppage for repairs, &c.

ST. GOTHARD TUNNEL—SOUTH END.

Results of Mechanical Perforation in the Advanced Gallery, during the Year ending September 30, 1874. Material—Mica-Schist.

Elements for Comparison. (Dubois and François' machines were used, assisted in the last quarter by MacKean's and Ferroux's machines.)	During the Three Months ending Dec. 31, 1873.	March 31, 1874.	June 30, 1874.	Sept. 30, 1874.	For the year ending Sept. 30, 1874.
Number of days	92	84[1]	91	91	35
	Metres.	Metres.	Metres.	Metres.	Metres.
Quarterly advance	181·1	167·2	159·8	173·0	681·1
Average daily advance	1·97	2·00	1·76	1·90	1·90
Maximum daily advance	3·90	3·70	3·50	4·50	4·50
Advance per attack or shift . . .	·80	·93	·89	·95	·89
Total number of attacks . . .	225	180	180	182	767
Number of attacks per day . . .	2·38	2·14	1·98	2·00	2·14
	h. m.	h. m.	h. m.	h. m.	h. m.
Average time to drill per attack . .	3.45	4.12	6.52	7.48	5.39
,, ,, to blast and clear away .	5.56	6.55	5.21	4.11	5.36
,, ,, from one attack to the next	9.41[2]	11.7	12.13	11.58[3]	11.15
Total number of holes bored . . .	3,602	3,165	3,860	4,691	15,318
Average number per attack . . .	16·0	17·6	21·4	25·8	20·0
	Metres.	Metres.	Metres.	Metres.	Metres.
Total length of all the holes . . .	4,050	3,692	4,659	5,501	17,902
Average total length per attack . .	18·0	20·5	25·9	30·2	23·4
,, ,, of a hole or an attack	1·13	1·17	1·21	1·17	1·17
Length of all the attacks . . .	253·0	209·9	217·8	213·0	897·4
Number of machines sent for repair .	108	131	202	286	727
,, ,, per attack . .	·48	·73	1·12	1·57	·95

[1] Excluding 5 days' working by hand. [2] Not including 35 hours' stoppage for repairs.
[3] Excluding 1 day for repairs.

It is further worth noting that, whilst the depth of the blasting holes averaged 1·07 metre, the actual advance gained only averaged ·96 metre, which was just nine-tenths of the depth of the holes. The number of attacks or shifts averaged more than $3\frac{1}{4}$ per day at the north end, in the end of the given year, whilst it did not exceed 2 per day at the south end. The improved progress that was made subsequently at the south end, was partly due to the substitution of Ferroux's perforator for Dubois and François' at the front, and partly to the cessation of the torrential influxes of water with which the south end was afflicted.

NORTH END.

Results of Mechanical Perforation in the Advanced Gallery, during the Three Months ending September 30, 1875.

Elements for Comparison. (Ferroux's machines were used.)	During the Month of July.	August.	September.	For the Three Months ending Sep. 30, 1875.
	Metres.	Metres.	Metres.	Metres.
Monthly advance	113·40	119·90	125·90	359·20
Average daily advance	3·66	3·87	4·20	3·91
Maximum daily advance	6·00	6·50	6·40	6·50
Advance per attack or shift	1·10	1·14	1·16	1·13
Total number of attacks	103	105	109	317
Number of attacks per day	3·32	3·39	3·63	3·45
	h. m.	h. m.	h. m.	h. m.
Number of hours of work	711.30	701.40	707.40	2,120.50
Time lost	30.20	42.40	12.10	85.10
Time of drilling headings	385.25	383.40	366.5	1,135.10
Time of blasting and clearing	326.5	318.0	341.35	985.40
Average time of boring a hole 1 metre long	1.3	1.5	1.3	1.4
Average time of boring per attack	3.45	3.39	3.21	3.35
Average time of blasting and clearing away, per attack	3·10	3.2	3.8	3.7
Average time from one attack to the next	6.55	6.41	6.29	6.42
Number of holes bored	1,844	1,773	1,752	5,369
Average number per attack	17·9	16·9	16·1	17·0
	Metres.	Metres.	Metres.	Metres.
Total length of all the holes	2,192·5	2,108·1	2,102·4	6,403·0
Average total length per attack	21·3	20·1	19·3	20·2
Average length of a hole or an attack	1·19	1·19	1·20	1·19
Length of all the attacks	122·5	124·8	130·8	378·1
Advance effected	113·4	119·9	125·9	359·2
„ „ per attack	1·10	1·14	1·16	1·13
Total length of holes, ineffective	162·1	82·7	78·8	323·6
„ per attack	1·57	·79	·72	1·03
„ per hole	·088	·047	·045	·060
Total number of machines employed	618	630	654	634
Average number of machines per attack	6	6	6	6
Number sent for repair	38	29	15	82
„ per attack	·37	·28	·14	·26
Proportion, per cent.	6·2	4·6	2·3	4·4

SOUTH END.

Results of Mechanical Perforation in the Advanced Gallery, during the Three Months ending September 30, 1875.

Elements for Comparison (Dubois' and François', and, for a part of the time, MacKean's drills were used).	During the Month of			For the Three Months ending Sept. 30, 1875.
	July.	August.	September.	
	Metres.	Metres.	Metres.	Metres.
Monthly advance	127·20	95·80	103·20	326·20
Average daily advance	4·10	3·09	3·44	3·54
Maximum daily advance	5·70	4·50	4·70	4·97
Advance per attack or shift	1·08	1·04	1·04	1·05
Total number of attacks	118	92	99	309
Number of attacks per day	3·81	3·00	3·30	3·37
	h. m.	h. m.	h. m.	h. m.
Number of hours of work	745.20	730.40	710.50	2,186.50
Time lost	—	17.50	7.50	25.40
Time of drilling headings	415.40	449.0	386.20	1,251.0
Time of blasting and clearing	329.40	281.40	324.30	935.50
Average time of boring a hole 1 metre long	1.15	1.55	1.29	1.33
Average time of boring per attack	3.31	4.53	3.54	3.53
Average time of blasting and clearing away, per attack	2.47	3.4	3.17	3.3
Average time from one attack to the next	6.18	7.57	7.41	7.19
Number of holes bored	2,045	1,487	1,635	5,167
Average number per attack	17·3	16·2	16·5	16·4
	Metres.	Metres.	Metres.	Metres.
Total length of all the holes	2,317·0	1·635·7	1,785·4	5,738·1
Average total length per attack	19·6	17·8	18·0	18·5
Average length of a hole or an attack	1·13	1·10	1·09	1·11
Length of all the attacks	133·7	101·2	108·1	343·0
Advance effected	127·2	95·8	103·2	326·2
" " per attack	1·08	1·04	1·04	1·05
Total length of holes, ineffective	111·8	87·3	80·9	280·0
" per attack	·95	·95	·82	·91
" per hole	·055	·059	·049	0·54
Total number of machines employed	826	644	693	721
Average number of machines per attack	7	7	7	7
Number sent for repair	58	61	43	162
" per attack	·41	·66	·41	·49
Proportion, per cent.	7·0	9·5	6·2	7·6

The performance of the perforators in the year 1875, during the three months ending September 30—just twelve months from the last quarter for which the operations are above reported—is summarised in the preceding tables, which are adjusted for comparison with the earlier tables.

Labour employed.—The average number of workmen employed on the works of the tunnel, from time to time, is exhibited in the following table, which gives the numbers employed from the commencement till January

31, 1876. The total number was gradually increased from 126, in October 1872, to 2,162 in January 1875.

ST. GOTHARD TUNNEL.

Number of Men employed at the Tunnel from the commencement of the Works till January 31, 1875.

Month.	North end.		South end.		Total.
	Average.	Maximum.	Average.	Maximum.	Average.
1872.					
October	64	102	62	152	126
November	97	125	132	179	229
December	101	120	171	203	272
1873.					
January	135	165	200	234	335
February	168	215	235	307	403
March	307	432	310	381	617
April	302	417	348	442	650
May	385	472	562	672	957
June	392	454	644	751	1,036
July	401	487	544	672	945
August	438	533	514	629	952
September	437	486	498	554	923
October	496	586	528	631	1,024
November	568	679	524	593	1,092
December	625	732	524	581	1,149
1874.					
January	634	686	581	612	1,215
February	603	684	569	612	1,172
March	750	884	622	709	1,372
April	782	943	704	838	1,486
May	889	1,037	930	1,120	1,819
June	750	856	1,024	1,220	1,774
July	913	1,047	1,180	1,362	2,093
August	1,011	1,130	1,120	1,340	2,120
September	1,011	1,097	981	1,190	1,992
October	—	—	—	—	—
November	963	1,077	924	1,107	1,887
December	984	1,107	978	1,135	1,962
1875.					
January	1,078	1,165	1,084	1,164	2,162
February	1,096	1,180	1,140	1,317	2,236
March	1,150	1,336	1,207	1,343	2,357
April	1,475	1,779	1,462	1,745	2,937
May	1,656	1,906	1,673	1,913	3,329
June	1,634	1,921	1,716	2,167	3,350
July	1,664	1,902	1,802	1,984	3,466
August	1,595	1,884	1,628	1,769	3,223
September	1,435	1,679	1,456	1,630	2,891
October	1,329	1,566	1,190	1,445	2,519
November	1,450	1,673	1,247	1,399	2,697
December	1,645	1,881	1,302	1,471	2,947
1876.					
January	1,685	1,875	1,394	1,488	3,079

NORTH END.

Principal results of numerous observations at the North end of the Tunnel.

Total depth from the mouth of the Tunnel.	Temperature at the front.	External temperature.	Difference of temperature.
Yards.	Fahrenheit.	Fahrenheit.	Fahrenheit.
11 } same day	35°	34°	+1°
109 } same day	48½	34	+14½
218 } same day	58	34	+24
338	69	54	+15
406	64	56	+8
486	59	45	+14
567	60	36	+24
622	62	30	+32
930 (April 1874)	66		
1,090 (June 1874)	67½		
1,180 (July 1874)	66½	61	+5½
1,410 (September 1874)	64½	59	5½
1,740 (December 1874) (270 yards below the surface.)	66½	28½	38
1,833 (January 1875)	68	37½	30½
1,930 (February 1875)	69	32	+37
" springs	63		
2,020 (March 1875)	67	38	+29
2,132 (April 1875)	68	48	+20
2,250 (May 1875)	69	58	+11
2,360 (June 1875)	69	64	+ 5
2,480 (July 1875)	71	62	+ 9
2,607 (August 1875)	70	63	+ 7
2,743 (September 1875)	73	56	+17
2,880 (October 1875)	72	56	+16
2,987 (November 1875)	75	29	+46
" springs	70		
3,084 (January 1876)	72	33	+39

to the soffit, 1½ metre, or 4 feet 10 inches, in diameter. The exhauster is connected to the outer end of the conduit, and draws not only the air discharged from the perforator, but also the gases produced by the blasting operations, and maintains a current of air from the mouth of the tunnel inwards to the workings.

From observations made in the gallery as soon as possible after a blast has taken place, it is estimated[1] that the cloud of smoke from the blast occupies a volume of from 320 to 400 cubic feet per pound of dynamite. The quantity of dynamite exploded is from 1·75 to 2·5 lbs. per cubic yard of rock

[1] According to *Engineering*, May 7, 1875, p. 380.

SOUTH END.

Principal results of numerous observations at the South end of the Tunnel.

Total depth from the mouth of the Tunnel.	Temperature at the front.	External temperature.	Difference of temperature.
Yards.	Fahrenheit.	Fahrenheit.	Fahrenheit.
54½	75°	86°	−11°
110	59	87	−28
164	55	44	+11
270	59	73	−14
397	52	63	−11
414	57	56	+1
454	54	59	−5
489	49	54	−5
514	52	39	+13
537	50	33½	+16½
567	56	42	+14
650	49	28½	+20½
812 (April 1874)	57½		
„ springs	50 to 52		
916 (May 1874)	57½		
982 (June 1874)	59		
1,044 (July 1874)	59	72	−13
1,110 (August 1874)	63½	65	−1½
1,170 (September 1874)	61½	59½	+2
„ springs	54½		
1,420 (December 1874)	65½	30	+35½
„ springs	59		
1,830 (January 1875)	66	40	+26
„ springs	59½		
1,631 (February 1875)	65	34	+31
1,730 (March 1875)	69	36	+33
(1,100 yards below the surface.)			
1,850 (April 1875)	69	52	+17
1,975 (May 1875)	69	59	+10
2,093 (June 1875)	70	58	+12
2,225 (July 1875)	70	72	− 2
„ springs	68		
(August 1875)	72	65	+ 7
(September 1875)	72	57	+15
(October 1875)	76	46	+30
(November 1875)	76	33	+43
(January 1876)	75	37	+38

removed. For an average daily progress of 13 lineal feet, at each end, on a cross sectional area of 630 square feet, the quantity of rock excavated per day is about 300 cubic yards; and, thence, the volume of smoke generated per day is estimated at, say $400 \times 300 = 120{,}000$ cubic feet, per day, or 83 cubic feet per minute. The air from the compressors alone is upwards of 40 times

as much as this. But, it is still further diluted by the action of the exhausters, which extract 16,500 cubic feet per minute—which is equal to a volume 200 times that of the exploded gases.

The bell-exhauster at each end consists of two systems of bells, connected by an oscillating beam, and balancing each other. Each system consists of a movable bell, 16 feet 5 inches in diameter, covering and surrounding a fixed bell, with a water-joint. It has a stroke of 4 feet 11 inches. Descending, a valve in the roof of the bell opens; ascending, it is closed, and a vacuum is formed under 5·9 inches of water, when air rushes into the ascending bell from the fixed bell. The volume of air withdrawn, for a complete oscillation of the two bells, is 2,060 cubic feet, corresponding, under 5·9 inches, to a volume of 2,000 cubic feet of vitiated air at atmospheric pressure. Supposing that 82 per cent. of the capacity of the bells is filled, the apparatus ought to make 10 oscillations per minute to exhaust the required quantity of air, 16,500 cubic feet per minute. The exhauster is driven by a double-action water-column apparatus, with two cylinders, one cylinder placed centrally within each fixed bell, and fixed to it. The piston is fixed to the movable bell, and is forced up by the water for the exhausting stroke. The cylinders and pistons at the north end, are 11 inches in diameter, and the efficiency is 53 per cent.; at the south end, they are 8·2 inches in diameter, being less than at the north end, for a greater head of pressure is available, and the efficiency is 50 per cent.

[The further history of the construction of the St. Gothard Tunnel, from 1876 until its completion in 1882, is given in Chapter XXVII., pages 350–363.]

PLATE XVIII

Scale 1/60

10 0 10 20 Feet

[Between pages [illegible] and [illegible].

NORTH END.


1 ADVANCED GALLERY
2 ENLARGEMENT OF GALLERY
3 MASONRY OF THE ARCH
4 CUTTING OF THE TRENCH
Level of the sleepers
5 COMPLETE EXCAVATION
Level of the sleepers

CHAPTER XXV.

COST OF TUNNELS.

THE cost of constructing tunnels varies extremely. It has been estimated that the tunnels formed for the old canals did not cost more than 4*l.* per lineal yard. For the ordinary gauge of railways, with a double line of way, the cost under the most favourable conditions—cutting through sandstone rock—may be as low as 20*l.* per lineal yard. Under a combination of unfavourable circumstances, the cost of railway tunnels has been as high as 125*l.* per yard. The Thames Tunnel need but be mentioned now—for it is a railway tunnel—and it cost 1,137*l.* per lineal yard.

Mr. Simms has given details of the cost of Blechingley Tunnel, which may be summarised as follows:—

COST OF BLECHINGLEY TUNNEL.

1,324 yards in length.

	Per yard. £	s.	d.		Per cent.
Materials	46	15	0	or	62
Labour—Mining	14	7	0	,,	19
Brickwork	8	16	0	,,	12
Miscellaneous	5	5	6	,,	7
Total cost	75	3	6	,,	100
Deduction for value of plant removed to Saltwood Tunnel	3	4	11		
Net cost	71	18	7	per lineal yard	

Here, it is to be remarked that the cost for labour in mining and brickwork, is half the cost for material; so that, excluding the miscellaneous charges, the cost for material is two-thirds, and the cost for labour is one-third of the whole cost.

Take, now, the items of cost of the Buckhorn Weston Tunnel, 739 yards long (detailed in a previous chapter), the total cost per lineal yard of which is the same as that of Blechingley Tunnel :—

COST OF BUCKHORN WESTON TUNNEL.

739 yards long.

	Per yard. £	s.	d.		Per cent.
Materials	30	1	0	or	42
Labour—Mining	28	1	0	„	38
Brickwork	8	6	0	„	12
Miscellaneous	5	10	0	„	8
Total cost	71	18	0	„	100

It appears that, whilst the cost for labour on brickwork and for miscellaneous work is practically the same as in the Blechingley Tunnel, the cost for labour in mining is doubled, and the cost for materials is a third less. The smaller cost for material may be accounted for by the absence of the invert; but, the double cost for labour in mining, is manifestly due to the troublesome rubbly rock that was met with, and the great influx of water which had to be contended with, in the Buckhorn Weston Tunnel.

The effect of the greater cost for mining labour is such as to invert the ratio of cost, for the charge for labour for mining and brickwork is two-thirds, and for materials one-third, of the whole cost, excluding miscellaneous charges .

Various useful details of labour and costs are given in previous chapters.

TABLE OF COST OF CONSTRUCTION OF VARIOUS TUNNELS, 1875.

Tunnel.	Railway.	Length.	Formation.	Cost per lineal yard. £	s.	d.
		Yards.		£	s.	d.
Blechingley	South Eastern	1,324	Clay	72	0	0
Saltwood	Do.	954	Sand	118	0	0
Buckhorn Weston	Salisbury and Yeovil	739	Clay	72	0	0
Lydgate	L. & N. Western	1,332	Coal measures	30	0	0
Guildford	South Western	965	Chalk	30	0	0
Salisbury	Do.	440	Do.	30	0	0
Petersfield	Portsmouth.	484	Do.	30	0	0
Honiton	Do.	1,350	Red marl and greensand	50	0	0
St. Catherine's	South Western	191	Sand	40	0	0
Clifton	Clifton Extension	1,737½	Limestone			
Lindal (enlargement)	Furness	460	Rock, gravel and clay, lined	21 38	4 0	0 0
Stapleton (do.)	Bristol and Gloucester	514				
Netherton (canal)	Birmingham	3,036	Marl	39	5	0
Loch Katrine	Glasgow Water Works	2,325	Mica-slate	13	0	0
			Clay-slate	£9 to £10		
			Old red sandstone	10	0	0
			Soft material, lined	10	0	0
Kilsby	L. & N. Western	2,398	—	125	0	0
Box	Great Western	3,123	Oolite, marl	100	0	0
Mont Cenis	Victor Emmanuel.	7·60 miles.	Calcareous schist, &c., estimated	167	12	0
St. Gothard	(In progress)	9·26 „	Granitic gneiss, &c.	116	9	0
Thames	East London	400 yards	Alluvial	1,137	0	0

CHAPTER XXVI.

VENTILATION OF TUNNELS.

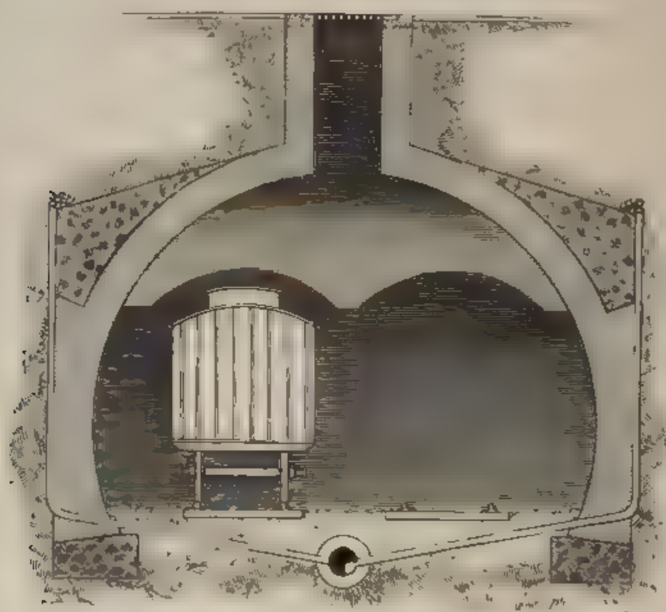
THERE are two conditions under which special provision is required to be made for the ventilation of tunnels: first, when the traffic is very great and very frequent through short tunnels, near the surface of the ground; second, where the tunnels are of great length, and are accessible for draught only at the ends.

The experience of the Metropolitan Railway, London, where trains travel every three or four minutes each way through tunnels, has conclusively demonstrated that, to effect ventilation by natural draught, open spaces, though they may be of short lengths, ought to be provided at frequent intervals for the circulation of air. When the line was opened and worked, it was quickly discovered that the natural ventilation of the section between King's Cross and Edgware Road Stations was quite inadequate to the requirements for changing the air of the tunnel, and additional openings were made, whilst the existing openings were enlarged. A large opening to the surface was cut about halfway between King's Cross and Gower Street Stations, and is now a block station. Again, at Gower Street, openings about 25 feet square were made down to the platforms. Portland Road Station, also, was opened upwards in two places; and Baker Street Station was opened to the external air by the making of the junction with the St. John's Wood Railway. In addition, openings upwards into the roadway, 25 feet long by 4 feet wide, had been cut at different points. Still, with the increasing traffic, the means of ventilation became deficient. Mr. Tomlinson, the Resident Engineer, made many observations and experiments with a view to improving the ventilation. His first efforts were made with anemometers, placed in various positions in the tunnel; but their very erratic and irregular performances, under seem-

ingly similar circumstances, gave no result of any value. He had recourse to naphtha lamps, hung about the tunnel in all possible positions, clear of the trains when passing. By close observation, he could trace a sensible current in the direction of the train, in front of it, near to or at the top of the tunnel; but at the lower and central portions no set current could be observed. The attempt was therefore made to discover to what extent this current at the top was affected by the openings in the roadway above, but no considerable discharge took place. A large bonfire of greasy waste and oil was kindled at the Edgware Road end of the tunnel, with a westerly breeze, by which the smoke was carried into and through the tunnel; but at the openings intended for ventilation scarcely a trace of the smoke could be observed escaping from them. The cloud of smoke and fume was, on the contrary, carried right through Baker Street and Portland Road Stations, and it was sensibly perceived at Gower Street Station. Mr. Tomlinson then proposed to intercept this current at the openings by fixing diaphragms across the upper part of the tunnel, clear of the trains, and so caused at least a portion, more or less, of the current to be expelled by the piston-like force of the trains. This contrivance, shown in the figures on next pages, was applied at thirteen points in the tunnel between Edgware Road and King's Cross; the results were good, for the atmosphere of the tunnel was decidedly improved. Besides driving out the foul air, the train, as it passed onwards, drew after it a very strong current of external air into the tunnel. The force of this current gradually decreased until the train had reached the next opening. The alternate upward and downward currents were generated at each opening on the passage of a train. A great improvement, also, was effected at the stations: before the screens were erected, each train that arrived at a station was followed by a current of foul air; but now it was to a great extent intercepted, and shunted by the screen into the upper air.

In the construction of the Metropolitan District Railway, openings to the outer air were provided at short intervals at, as well as between, the stations. The longest covered section of this railway is the tunnel between Westminster Bridge and St. James's Park Stations, 221 yards, or an eighth of a mile. With such facilities for the removal of foul air, discharged from trains which

pass each way every three minutes during the busy hours of the day, the atmosphere of the tunnels on the District Railway is sufficiently good for every practical purpose. At the same time it must be remarked that, in heavy winter weather, the tunnels are filled—in the upper parts at least—with lingering vapour, which, in the absence of atmospheric currents, emerges but slowly into the open air. The sluggishness of what may be called spontaneous ventilation, is obviously to be explained by the very low 'head,'



METROPOLITAN RAILWAY.—TRANSVERSE SECTION OF THE TUNNEL, SHOWING THE VENTILATING DIAPHRAGMS.

or column of heated air, which is limited by the surface of the ground over the ends of the tunnels. But when the wind blows in the direction of any section of tunnel, or nearly in the same direction, a thorough draught is set up from one to the other, and the ventilation is thereby accelerated.

Many schemes have been broached for employing the moving trains as ventilators, by causing them to drive out the foul air before them, and necessarily drawing in a supply of fresh air behind them. Without specifying these proposals, it may only be said that the method of the diaphragm employed by Mr. Tomlinson on the Metropolitan Railway, though very

limited in the scope of its action, is the only one that has been practically carried out. It is, no doubt, well adapted for tunnels near to the surface of the ground; and it might probably also be employed with benefit wherever there are permanent open shafts from the tunnel to the surface, even where the surface is very much above the tunnel. In such tunnels, of which some examples have been detailed in preceding pages, the shafts are spaced at intervals of about 200 yards; and it has been proved by the experience of

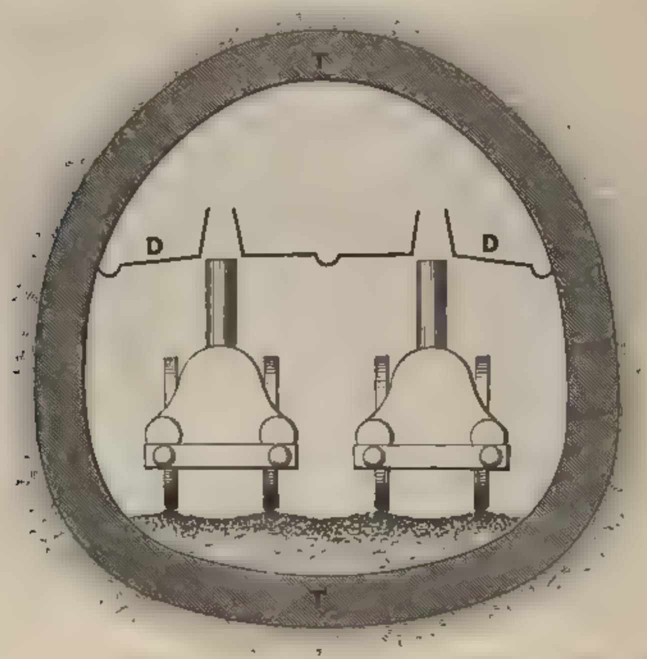
METROPOLITAN RAILWAY.—LONGITUDINAL SECTION OF THE TUNNEL, SHOWING THE VENTILATING DIAPHRAGMS.

the Metropolitan lines that at intervals of such length, artificial ventilation derived from the movement of the trains would be amply sufficient. In adapting the diaphragm (shown in the figures), to deep shafts, these would require to be divided by a brattice, to ensure the continued upward flow and ultimate discharge of the foul air, and the corresponding downward influx of fresh air—separating the currents and preventing their mixing with and baffling each other.

On another principle of ventilation, Mr. W. H. Barlow has proposed that the upper portion of the tunnel, above the level of the train, should be

separated from the lower portion by horizontal partitioning, as in the figure annexed.

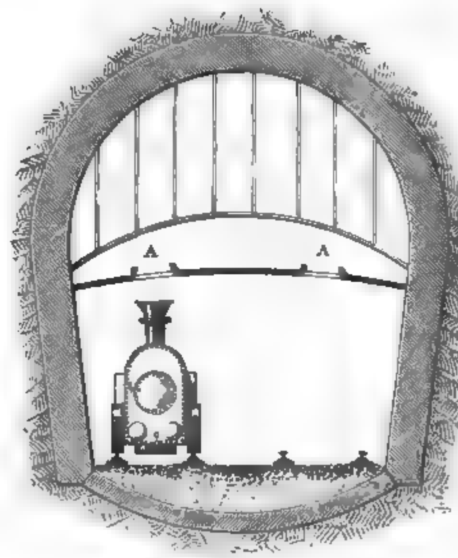
In the partition, D D, there are openings over the line of the chimneys of the locomotives, the sides of which are from 18 inches to 2 feet high, and inclined inwards. The products of combustion, projected from the engines, would be driven into the upper chamber, where they would be detained, and thus prevented from mixing with the other air in the tunnel. The foul air,



VENTILATION OF TUNNELS.—HORIZONTAL BRATTICE, D D, PROPOSED BY MR. W. H. BARLOW.

he anticipates, would make its escape naturally from 'tunnels of moderate length.' In tunnels of great length, without shafts, there is no doubt that the employment of artificial means of extracting the foul air from the upper chamber would be necessary; though it is conceivable that in the use of pumps or fans for this purpose, as much air, or even more air, would be drawn from the lower part through the free openings in the diaphragm, as from the upper chamber. A more nearly complete separation would be required, and Mr. Longridge proposes the introduction of a double diaphragm, as in the annexed figure, leaving a space, A A, between the diaphragms, into which the

ejected gases should pass. The upper diaphragm should be divided longitudinally into sections, say 1 inch in length, each section to be connected with one of a number of air-ducts, constructed by dividing the space above by vertical partitions in the direction of the tunnel. Each duct is to be in exclusive communication with a section of the tunnel, in order that the foul air from such section may be exhausted independently of the air from other sections. This expedient of subdivided communication is proposed to be employed for the purpose of ensuring the removal of foul gases simultaneously from all parts of the tunnel alike.



VENTILATION OF TUNNELS BY BRATTICED DRIFTWAYS.—MR. LONGRIDGE'S SCHEME.

Mr. V. G. Bell, in enunciating the principle of separate ventilation for successive sections of a long tunnel, proposes that the isolated conduits for foul air should be built into and form an integral portion of the walls and the arch of the tunnel.[1]

General Principles of the Ventilation of Tunnels.—It appears that the ventilation of long and close tunnels, without any intermediate openings, worked by steam-locomotives, can only be effected by artificial means—extracting the foul air from every portion of the tunnel. This may be done on either of two systems: the separate system, as it may be called, in which the refuse gases are collected apart from the general air of the tunnel, isolated and abstracted; or the dilution system, as it may be called, in which the refuse gases are mixed with the air of the tunnel, and the whole of the diluted mixture is extracted. Here is a most important distinction; for, in the first system, the volume to be extracted per minute is not a hundredth

[1] The above particulars and illustrations are derived from the *Proceedings of the Institution of Civil Engineers*, vol. iv., 1876, 'The Ventilation and Working of Railway Tunnels,' by Mr. G. J. Morrison.

part of the volume required to be extracted on the second system; and the mechanical power required to effect a thorough ventilation in the first system is an exceedingly small proportion of that which would be required on the second system. At the same time, the first system, besides being much the more economical in power, possesses the advantage of being a positive system, capable of maintaining absolutely pure the atmosphere of the tunnel; whilst, on the second system, this atmosphere can never be absolutely pure, though it may of course, by a large expenditure of power, be maintained at a fair degree of pureness.

To provide the materials for a direct comparison, it is scarcely needful to take account of the quantity of air consumed by the respiration of passengers in a train passing through a tunnel, for this constitutes but an insignificant proportion of the whole quantity of air consumed and converted into poisonous gases by the locomotive. Take an average consumption of 35 lbs. of coal per mile run by each train through the tunnel, the volume and weight of gases produced by the complete combustion of coal of average composition are as follows:—

	Cubic feet, at 62° F.	Pounds.
Carbonic acid	25·2	2·93
Steam, gaseous	9·5	·45
Sulphurous acid	0·15	·025
Nitrogen	115·29	8·536
	150·14	11·94

Say, in round numbers, 150 cubic feet, or 12 lbs., of gaseous products of combustion, per pound of coal, amounting to (150 × 35 =) 5,250 cubic feet, or to (12 × 35 =) 420 lbs. of gaseous products per mile of tunnel.

These data give, in round numbers, 1 cubic foot of gaseous products per lineal foot of tunnel traversed by a train.

Also, ·08 or $\frac{1}{12}$ lb. of gaseous products per lineal foot of tunnel traversed by a train.

An ordinary tunnel for a double line, 26 feet wide and 21 feet high, has a sectional area of 473 square feet; or it contains, when clear of foul gas,

473 cubic feet of air per lineal foot of tunnel. The weight of this volume of air at 62°, at the rate of ·0761 lb. per cubic foot, amounts to 36 lbs

Again, the quantity of steam discharged from the locomotive for each pound of coal is, say $8\frac{1}{2}$ lbs., occupying, at atmospheric pressure, a volume equal to 26·36 cubic feet per pound weight; or a total of 224 cubic feet for each pound of fuel. Supposing that this steam is diffused, uncondensed, amongst the air and other gases, the quantity to be collected amounts to $(224 \times 35 =)$ 7,840 cubic feet, or to $(8\frac{1}{2} \times 35 =)$ 297 lbs. per mile of tunnel.

That is, in round numbers, $1\frac{1}{2}$ cubic feet of steam, at atmospheric pressure, per lineal foot of tunnel traversed by a train.

Also, ·056 or $\frac{1}{18}$ lb. of steam per lineal foot of tunnel traversed by a train.

On the basis of the foregoing data, the following general proportions may be accepted for the air, gaseous products, and steam constituting the atmosphere of a tunnel without draught, traversed by one train:—

In Tunnel.	Per Lineal Foot.			Per Lineal Mile.		
	Cubic feet.		Pounds.	Cubic feet.		Pounds.
Air	473	or	36	2,497,440	or	190,080
Gaseous products . .	1	"	0·08	5,250	"	420
Steam	1·5	"	0·056	7,840	"	297

Here, the gaseous products and steam together, for one train, amount, in volume, to $2\frac{1}{2}$ cubic feet per lineal foot of tunnel, or 13,090 cubic feet per lineal mile, being about one-half per cent., or $\frac{1}{192}$ fraction, of the volume of the tunnel. The quantities corresponding to the number of trains per hour passing both ways through the tunnel are, therefore, in round numbers, as follows:—

GASEOUS PRODUCTS AND STEAM, PER MILE PER MINUTE.

Trains per hour, both ways.	Volume of air, or Capacity of Tunnel per mile.		Gaseous Products and Steam per mile of Tunnel per minute.			
	Volume.	Weight of air, at 62°.	Volume at 62°.	Parts of volume of the air.	Weight.	Parts of weight of the air.
	Cubic feet.	Pounds.	Cubic feet.	Fraction.	Pounds.	Fraction.
2	2,500,000	190,000	438	$\frac{1}{5708}$	24	$\frac{1}{7920}$
4	2,500,000	190,000	876	$\frac{1}{2854}$	48	$\frac{1}{3960}$
8	2,500,000	190,000	1,752	$\frac{1}{1427}$	96	$\frac{1}{1980}$
16	2,500,000	190,000	3,504	$\frac{1}{713}$	192	$\frac{1}{990}$
32	2,500,000	190,000	7,008	$\frac{1}{356}$	384	$\frac{1}{495}$

If, then, the ventilation is to be effected entirely by artificial means, the whole of the air and products are, on the dilution system, to be drawn from the tunnel at such a rate as will confine the proportion of impurity in the atmosphere of the tunnel within harmless limits; whilst, on the separate system, if strictly effected, gaseous matters having only $\frac{1}{5700}$th part of the bulk of the air, are to be extracted, when there are two trains per hour, both ways; or a greater proportion, rising to $\frac{1}{356}$th of the bulk of the air, for 32 trains both ways per hour. The last limit, giving an average of one train every two minutes, approaches nearly to the practice on the Metropolitan underground railways.

In forming an estimate of the quantity of ventilation that would be required on the dilution system, it is to be remarked that the proportional quantity of carbonic acid in the air of a tunnel may be taken as an index to its general character for purposes of respiration. The normal quantity of carbonic acid in the atmosphere is, according to the analyses of Dr. Angus Smith, from 3 to 4 parts in 10,000; say $3\frac{1}{2}$ parts in 10,000, on an average. Nevertheless, the proportion in many situations greatly exceeds this ratio.

Dr. A. Smith found by analysis that the atmcspheres of the following localities contained the annexed proportions of carbonic acid :—

	Carbonic acid. Volumes in 10,000 parts of air.
In the streets of Manchester, during fog	6·8
In the dress circle, Haymarket Theatre, 1864	7·6
In close buildings, average	16·0
In the pit of the Theatre Royal, Manchester	27·3
In the worst parts of theatres	32·0
In mines (average of 339 tests)	78·5
In mines, largest proportion	273·0

Here, the margin for excess is very wide. Dr. Letheby states that whilst, with a proportion of 10 in 10,000 the atmosphere begins to get bad, there are many instances in which persons lived, apparently without discomfort, in an atmosphere holding considerably more than 15 volumes of carbonic acid in 10,000 of air; and he considers that if a tunnel can be traversed in an hour, or two hours, the atmosphere might, with safety, contain 15 volumes in 10,000. In support of this estimate, he states that, when tested—

	Carbonic acid in 10,000 volumes of air.
The Court of Chancery contained	19·8 volumes.
The Chamber of Deputies in Paris	25 "
The London theatres	10·2 "
The Paris theatres	23 to 43 "

Adopting, then, as a limit for tunnel atmospheres, the measure of 15 volumes of carbonic acid in 10,000 volumes of air, the quantity of carbonic acid ejected by the locomotives, and pervading the air of the tunnel, is not to exceed the difference of the limiting quantity and the normal quantity in the atmosphere, or $(15-3{\cdot}5=)$ 11·5 volumes in 10,000 volumes of air. Now, it is seen from the composition of the gaseous products of the combustion of coal (page 336), that the proportion of the constituent carbonic acid is one-sixth by volume and one-fourth by weight of the total products; and it follows, by simple multiplication, that the limiting proportion of the whole of the gaseous products of combustion is $(11{\cdot}5\times 6=)$ 69, or, say, 70 volumes in 10,000. In addition, there are $1\frac{1}{2}$ volumes of steam from the engine for every volume of

gaseous products, or ($70 \times 1\frac{1}{2} =$) 105 volumes of steam in 10,000 of air; making up a total of gaseous products and steam, equivalent to ($70 + 105 =$) 175 volumes in 10,000 volumes of air, as the limiting proportion, or 1 in 57.

To apply this ratio to the discharges of gas and steam, given in the table (page 340), it was there shown that for two trains per hour, both ways, the discharge was equivalent to 1 volume in 5,708 of air, per mile of tunnel per minute, or to $\frac{57}{5708}$ parts, or $\frac{1}{100}$th of the limiting proportions. It would follow that, in order that the proportion of impurities may not exceed the permissible limit, the air of the tunnel should be entirely changed every 100 minutes, or every $1\frac{2}{3}$ hours. Correspondingly, the times in which the air of the tunnel should be entirely changed for various numbers of trains per hour, are as follows:—

VENTILATION THROUGH THE ENTIRE SECTIONAL AREA OF THE TUNNEL.

Trains per hour, both ways.	Discharge per mile per minute, in parts of the limiting proportion.	Time in which the air of the Tunnel should be entirely changed.	Required rate of velocity of the current per mile of length of traverse.	
		Minutes.	Feet per min.	Miles per hour
2	$\frac{57}{5708}$ or $\frac{1}{100}$	100	52·8	0·6
4	$\frac{57}{2854}$ or $\frac{1}{50}$	50	105·6	1·2
8	$\frac{57}{1427}$ or $\frac{1}{25}$	25	211·2	2·4
16	$\frac{57}{713}$ or $\frac{1}{12 \cdot 5}$	$12\frac{1}{2}$	422·4	4·8
32	$\frac{57}{356}$ or $\frac{1}{6 \cdot 25}$	$6\frac{1}{4}$	844·8	9·6

In the last two columns is added the rate of velocity of the current, supposing that the current traverses the entire sectional area of the tunnel, per mile of length of tunnel, necessary for entirely changing the air within the time prescribed in the third column. From these data, the required velocity of the current, for any given length of tunnel to be traversed, is found by multiplying the tabular velocity by the length of traverse. For example, if a tunnel 10 miles in length, traversed by two trains per hour, both ways,

is to be ventilated by the withdrawal of the air from one end, the velocity per mile of length is 0·6 miles per hour, and $0·6 \times 10 = 6$ miles per hour, the velocity of the ventilating current. In this manner, the velocities for ventilation have been calculated in the following table, for lengths of tunnel from a quarter mile to twenty miles:—

VELOCITY OF VENTILATION

Through the entire Sectional Area of the Tunnel.

Trains per hour both ways.	Required velocity of current per mile of length of tunnel.	Total velocity of the current in Miles per hour. Total length of Tunnel, in Miles.										
		¼	½	¾	1	2	4	6	8	10	15	20
Trains.	Miles per hour	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.
2	0·6	0·15	0·30	0·45	0·6	1·2	2·4	3·6	4·8	6·0	9·0	12·0
4	1·2	0·30	0·60	0·90	1·2	2·4	4·8	7·2	9·6	12·0	18·0	24·0
8	2·4	0·60	1·20	1·80	2·4	4·8	9·6	14·4	19·2	24·0		
16	4·8	1·20	2·40	3·60	4·8	9·6	19·2	28·8				
32	9·6	2·40	4·80	7·20	9·6	19·2						

Many of the higher velocities are, though not impossible, at least impracticable. For the longer tunnels, the limit is reached when traversed by four or eight trains per hour, both ways. For the probable case of a tunnel under the English Channel, 20 miles long, traversed by only two trains per hour both ways—that is, by one train each way per hour—the required velocity of a thorough draught is, by the table, 12 miles per hour. This calculation is corroborative of the estimate of Mr. Cowper, who considered that a velocity of current of 12½ miles per hour would suffice for the thorough ventilation of a tunnel 25 miles in length, traversed by trains at intervals of one hour each way. For the same length of tunnel, and number of trains, the editor's rule would require a velocity of 15 miles per hour, which is in excess of Mr. Cowper's estimate; but probably Mr. Cowper adopted a lower consumption of fuel than 35 lbs. per mile as the basis of his estimate.

The pressure necessary to maintain ventilation in a tunnel, is expressed by

the formula, based upon the observation of various experimentalists, quoted by Mr. Morrison, on the frictional resistance of air in conduits :—

$$h = \frac{V^2PL}{633,000\ A} \quad \text{(1)}$$

$$\text{also, } V^2 = \frac{633,000\ Ah}{PL} \quad \text{(2)}$$

h = the head of pressure, in inches of water.

V = the velocity of the current in feet per second.

P = the perimeter of the tunnel, in feet.

L = the length of tunnel traversed, in feet.

A = the sectional area of the tunnel, in square feet.

The density of the air is assumed to be at the rate of ·076097 lb. per cubic foot, which is the density of dry air at 62° F.; or $\frac{1}{820}$th part of the density of water taken at 62·4 lbs. per cubic foot.

The value of the effective work done within the tunnel, in horse-power, in terms of the head, the velocity, and the sectional area, is found by the following formula, based on the datum that 1 inch of water is equivalent to a pressure of 5·20 lbs. per square foot :—

$$H = \frac{VAh}{106} \quad \text{(3)}$$

in which H = the horse-power and, by substituting, in this formula, the value of h (formula 1) and reducing :—

$$H = \frac{V^3PL}{67,000,000} \quad \text{(4)}$$

By means of this formula, the net horse-power of useful work done is found in terms of the velocity, the perimeter, and the length only.

The engine power required to effect the ventilation, by means of suitable machinery, may be taken at 2½ times the net horse-power, to include an approximate allowance for the power consumed in the approach to the ventilator. Then,

$$H, = \frac{V^3PL}{27,000,000} \quad \text{(5)}$$

in which H, = the total indicator horse-power required.

By means of the last formula (5), the gross indicator horse-power required

to ventilate the lengths of tunnel specified in the preceding table are given in the following table. The velocity in feet per second, it may be mentioned, is approximately equal to $1\frac{1}{2}$ times the velocity expressed in miles per hour; and it has been so assumed in making the following calculation; for which the value of P, the perimeter, is taken at 83 feet:—

TOTAL INDICATOR POWER REQUIRED

For Artificial Ventilation through the entire sectional area of the Tunnel.

Trains per hour both ways.	Indicator Horse-Power. Limit of Impurity—15 Volumes of Carbonic Acid in 10,000 Volumes of Air.										
	Total length of Tunnel, in Miles.										
	¼	½	¾	1	2	4	6	8	10	15	20
Trains.	H. p.	H. p.	H. p.	H. p.	H. p.	H. p.	H. p.	H. p.	H. p.	H. p.	H. p.
2					0·2	3	15	48	118	625	1,900
4				0·1	1·5	24	120	388	946	5,000	15,140
8			0·27	0·8	12	192	960	3,104	7,568		
16		0·4	2·2	6·4	96	1,536	7,680				
32	0·2	3·3	16	51	768	12,288					

In the shorter lengths of tunnel, natural ventilation comes into play, and it may occasionally, to some extent, supersede artificial ventilation. The rapid increase of power necessary for artificial ventilation, in proportion to the length of the tunnel, is very remarkable. The increase, in fact, takes place in the ratio of the 4th power of the length; so that a tunnel 20 miles long requires 10,000 times the power for ventilation required for a tunnel 2 miles in length; though it may be that the shorter tunnels should be provided with a little more power than what is given by the formula.

It is remarkable, further, that the power increases very rapidly with the increase in the number of trains traversing the same length of tunnel. It increases, in fact, as the cube of the number of trains, insomuch that by doubling the number of trains traversing a 2-mile tunnel from 16 to 32 per hour both ways, the required power, which is 96 indicator horse-power with

16 trains, rises to 768 horse-power with 32 trains. In a 20-mile tunnel, similarly, the power rises from 1,900 horse-power for two trains per hour, to 15,000 horse-power for four trains per hour.

In view of these deductions from experimental data, which, though the means of verification have not yet been supplied by actual practice, are yet sufficiently salient to command the careful study of engineers, it is well now to direct attention to the expedients which have been proposed for ventilation on the separate system, and to form an estimate of the power required for it.

It was shown in the table, page 338, that the volume of gaseous products and steam discharged into the tunnel per mile per minute, increased uniformly from 438 cubic feet for two trains per hour both ways, to 7,008 cubic feet for 32 trains per hour.

The simplest application of the separate system consists in the employment of an upper chamber or driftway, formed in the upper part of the tunnel by a horizontal brattice, extending from one end of the tunnel to the other, into which the gases and steam are discharged, direct from the chimney of the locomotive, in a manner similar to that illustrated at pages 334 and 335, through longitudinal apertures, which are marked A A in page 335. Let an additional interior horizontal brattice be erected, as illustrated in the same fig., but without any vertical diaphragms. The upper brattice will then enclose a free driftway, which may be assumed to be a circular segment, 5½ feet high and 20 feet wide at the level of the brattice, with a clear sectional area of about 60 square feet. Let numerous openings be formed in the upper brattice, for the transmission of the gases from the interspace into the driftway. Thus, the gases so separated from the atmospheric air of the tunnel can be withdrawn by exhausting machinery placed at each end of the tunnel. On this system, the tunnel would be ventilated from the middle towards the ends. The areas of the openings through the upper brattice would require to be adjusted so that the in-draught at all points of the tunnel should be just sufficient directly to withdraw the gaseous discharge into the interspaces. For the attainment of such uniform suctional action, the allowance of passage-way through the upper brattice, per yard run of the tunnel, should be a maximum

at the middle of the tunnel, where the suctional force is weakest, and a minimum at each end, where the suctional force is greatest, being properly graduated between the middle and the ends.

It was shown at page 339 that the volume, at 62° F., of the gaseous products and the steam together, discharged into the tunnel, is 2½ cubic feet per lineal foot of tunnel per train. That is, a continuous stream of gases, having a volume measured by 2½ square feet in section, is discharged by each locomotive. The driftway, having a sectional area of 60 square feet, would therefore be capable of holding (60÷2½=) 24 streams of gases abreast, or the discharge from 24 trains.

It follows that the average velocity of the exhaust current through the driftway, should be such that the current may traverse the half-length of the tunnel in the same period of time in which 24 trains enter the tunnel. In a tunnel 8 miles long, for example, traversed by 16 trains both ways per hour, 24 trains would enter the tunnel in 1½ hours, and it would be necessary that the current should traverse the half-length of the tunnel, 4 miles from the middle, towards each end, in 1½ hours; or at an average velocity of (4÷1·5=) 2·7 miles per hour. In the same way, the average velocities have been calculated for various trains and lengths of tunnel, as given in the following table:—

REQUIRED AVERAGE VELOCITY OF VENTILATION OF A TUNNEL

By Bratticed Driftway.

Trains per hour, both ways.	Required average velocity of current per mile of tunnel.	Total average velocity of the current, in miles, per hour.										
		Total length of Tunnel, in Miles.										
		¼	½	¾	1	2	4	6	8	10	15	20
Trains.	Miles per hour.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.	M. p. h.
2	0·042	0·01	0·02	0·03	0·04	0·10	0·17	0·25	0·35	0·42	0·65	0·85
4	0·085	0·02	0·05	0·07	0·08	0·17	0·34	0·5	0·7	0·85	1·3	1·7
8	0·17	0·04	0·09	0·13	0·17	0·34	0·68	1·0	1·4	1·7	2·6	3·4
16	0·34	0·08	0·17	0·26	0·34	0·68	1·35	2·0	2·7	3·4	5·1	6·8
32	0·70	0·17	0·35	0·5	0·7	1·4	2·7	4·1	5·4	6·8	10·2	13·6

It may be observed that these average velocities are only one-fourteenth of those required for ventilating through the entire sectional area of the tunnel, page 343.

But, in order to calculate the total indicator horse-power required to perform these ventilations, it is necessary to ascertain the average head or pull of the current, which is that due to the mean square of the uniformly accelerated velocities of the current from the middle of the tunnel to each end. The maximum velocity—namely, that at the end of the tunnel—being taken as 1, the head is that due to a velocity of ·5775 ; or, if the average actual velocity, which is half of the maximum, be taken as 1, the head is that due to a velocity of (·5775 × 2 =) 1·155. If the tabulated velocities, therefore, be put equal to V, then 1·155 V is to be substituted for V in the formula (1), to find the head; and 2 V, the terminal velocity, is to be substituted for V in formula (3). Consequently, in formula (4), the co-efficient ($1·155^2 \times 2 =$) 2·67 is to be prefixed to V; and, by reduction, the formula becomes—

$$H \; \frac{V^3PL}{25,100,000} \qquad (6)$$

for the net horse-power of useful work done in the drift. Similarly, formula (5) becomes—

$$H, = \frac{V^3PL}{10,000,000} \qquad (7)$$

for the total indicator horse-power required. This power is to be divided into two, one-half to be applied at each end of the tunnel.

With the formula (7), the total indicator horse-powers in the following table are calculated, the perimeter P being equal to 45 feet.

Here the power necessary to ventilate the tunnel by a brattice driftway, on the separate system, is an infinitesimal fraction of that which is required to ventilate through the entire sectional area of the tunnel. Conclusive evidence is afforded that the separate system of ventilation is to be the method of the future. It affords a complete solution of the problem of the perfect and economical ventilation of the Metropolitan Railway—in potentiality and economy of outlay far surpassing any natural system of ventilation. Likewise, and with equal facility, it affords a complete solution of the problem of the ventilation of the projected Channel Tunnel, 22 miles in length.

TOTAL INDICATOR POWER REQUIRED

For Artificial Ventilation of Tunnel by a Bratticed Driftway, on the separate system.

Trains per hour, both ways.	Indicator Horse-Power. Two traverses, each equal to half length of Tunnel. Total length of Tunnel, in Miles.										
	¼	½	¾	1	2	4	6	8	10	15	20
Trains.	H. p.	H. p.	H. p.	H. p.	H. p.	H. p.	H. p.	H. p.	H. p.	H. p.	H p.
2										0·28	0·9
4								0·2	0·45	2·2	7
8						0·1	0·5	1·6	3·5	18	56
16						0·7	4	12·6	28	142	450
32					0·36	5·7	30	100	225	1,140	3,600

No notice has been taken of the aid that may be afforded by natural ventilation, in conjunction with artificial ventilation, for it is capricious and changeable, and it may even at times hinder the action of artificial means of ventilation. It cannot, therefore, be taken into calculation. Very possibly, the lower powers in the preceding tables are understated; but, taken as a whole, the data supplied may be accepted as approximate measures of the conditions under which the ventilation of tunnels is to be effected.

CHAPTER XXVII.

TUNNELLING IN HARD ROCK.

ST. GOTHARD TUNNEL (1876 TO 1882).[1]

THE progress made with this tunnel from 1872 to 1875, when about two-thirds of the work remained to be performed, is detailed in the earlier edition of this book, published in 1877 (see pp. 277 to 328). In October 1875 the axis of the tunnel was verified from the observatories which were stationed at each end. A portable electric apparatus on Morse's system was employed, by which telegraphic communication was maintained between the observatories and the stations within the tunnels, and the operations were thus considerably accelerated. The deviations were found to be as under:—

NORTH END.	SOUTH END.
At 1,745 yards, 3 inches eastward	At the entrance, $\frac{1}{10}$ inch eastward
„ 2,290 „ $4\frac{3}{4}$ „ „	„ 1,430 yards, 1·6 „ „
„ 2,620 „ 6 „ „	„ 1,680 „ 1·6 „ „
	„ 2,250 „ 2 inches westward

The length of the tunnel as remeasured was found to be less by 27 inches.

The work of boring was prosecuted with all speed on the lines already described until, at November 30, 1878, the advanced heading had penetrated to a distance of 6,811 yards at the north end and of 6256·7 yards at the south end, making together 13,067·7 yards, or 7·42 miles, equivalent to a net progress of $4\frac{1}{2}$ miles in 3·3 years, or 6·64 yards per day, during this period. The average progress, however, for the last eleven months, ending November 30, 1878, amounted to 7·5 yards per diem.

The strata of the calcareous basin of Andermatt, about 3,000 yards from the north end of the tunnel, were traversed in the last three months

[1] Continued from p. 328.

of 1875. The gneiss of the valley of the Urseren, very compressible and disintegrated, could be traced to a distance of about 2,800 yards inwards. Streams of water issued through numerous fissures in the rocks near the head, at the rate of 180 gallons per minute, the total discharge from the tunnel at this period amounting to 290 gallons per minute. The limit of the strata belonging to the basis of the Urseren valley on the one part and the body of the St. Gothard on the other, was reached at a distance of between 4,500 and 4,900 yards. Up to this point, the rock consisted of green schist, or Urseren gneiss rock, but beyond this, the micaceous gneiss of the type of Gurschen, and which is characterised by brown mica, was met with. The green schist was of different degrees of hardness and compactness, but was, on the whole, easily excavated; but it required frequent timbering for support, in consequence of its tendency to exfoliate and thus to detach itself in pieces. Water was freely discharged, and in March and April it flowed at the rate of 450 gallons per minute. Serpentine rock was reached at 5,300 yards; and though not very hard it was difficult to work, on account of its extreme tenacity. When the depth reached 5,440 yards the discharge of water did not exceed 240 gallons per minute.

At the south side, between 2,500 and 2,800 yards in depth, many varieties of laminated mica-schist were penetrated, and were excavated without difficulty. At 2,700 yards, in November 1875, the last beds of schist belonging to the basin of the Grasso di Fondo were traversed. From this point, the rock was in a state of decomposition, and was very compressible. Through one fissure, water was ejected with such force as to break away and carry off considerable fragments of rock. Further on, at a depth of 3,000 yards, the rock became regular in structure, and was easily extracted. Hornblende followed. At 3,500 yards micaceous gneiss was reached, forming the commencement of the St. Gothard gneiss. The discharge from the gallery in the last three months of 1876 varied from 2,760 to 3,060 gallons per minute, whereas in November 1875 it amounted to 3,360 gallons per minute. The comparatively diminished flow in 1876, appears to confirm the theory that the discharge of water in the gallery depends entirely upon the quantity falling at the external

surface. At 4,560 yards, simple gneiss rock was reached, and it extended, with some variations in quality, as far as the face of the heading in November 1878.

A table is appended showing the annual progress made in the headings up to this period.

TABLE SHOWING YEARLY PROGRESS OF THE HEADINGS TO NOVEMBER 30, 1878.

Total length of tunnel from entrance at Göschenen to that of temporary tunnel at Airolo, 16,317 yards.

—	Yearly Advance.		
	North End. Göschenen.	South End. Airolo.	Total.
	By hand. Yards.	By hand. Yards.	By hand. Yards.
1872	20·7	111·2	131·9
1873	76·3	128·5	204·8
1875	21·0	—	21·0
1876	50·3	—	50·3
Total by hand	168·3	239·7	408·0
	By machine.	By machine.	By machine.
1873	559·4	412·1	971·5
1874	1134·1	817·4	1951·5
1875	1262·3	1373·1	2635·4
1876	1049·6	1116·1	2165·7
1877	1345·7	1087·2	2432·9
January to November 1878	1291·6	1211·1	2502·7
Total by machine	6642·7	6017·0	12659·7
Total by hand and machine	6811·0	6256·7	13067·7

The rock drills, or perforating machines, of Ferroux, Dubois and François, and McKean were employed in the advanced galleries until November 1875, subsequent to which date Ferroux's machines were used exclusively at the north end, and McKean's machines exclusively at the south end.

In 1876 M. Ferroux simplified his machine, the principle of automatic action by the pressure of the air being retained, whilst substituting for the

heavy mechanism, simpler means of distributing the air and turning the drill. The perforator was then reduced nearly one-half in weight and cost, the weight when reduced being less than 400 lbs. The calculated volume of air consumed per stroke of the drill was 85 cubic inches. A new carriage was introduced by M. Ferroux in 1877, which was so arranged, that the broken rock could be removed on narrow lines of rails, one at each side of the machine, without removing it, and without exceeding a width of 8½ feet for the gallery. It weighs nearly 2·4 tons.

In 1877, the McKean drill was modified by M. Sequin so as to supersede the spirally grooved cone and cylinder of the machines as already described, and which were reported to be subject to rapid wear, by a spiral groove cut in the spindle between the double cone and the tool-holder. The stroke of the piston is about 4¾ inches, its diameter 4 inches, and its rod is 2·4 inches in diameter. Under a pressure of one atmosphere, from 450 to 480 strokes per minute can be made, penetrating 6 inches into the St. Gothard granite. Four new and similar groups of turbines and compressors were erected in the summer of 1876, two in Göschenen and two at Airolo. In each group there was comprised (1st) a Gerard turbine, 16 feet 7 inches in diameter, on a horizontal shaft, under a clear head of 240 feet, and yielding 325 horse-power at the shaft, by the expenditure of 1,016 cubic feet of water per minute, at a speed of 70 revolutions per minute; and (2nd) two air pumps, each on a frame which carries one end of the turbine shaft, the turbine being placed between the pumps. The pumps are worked by cranks and connecting rods from the turbine shaft. Each pump is 27½ inches in diameter, with a stroke of 35·4 inches, and the air is compressed to 8 atmospheres of total pressure. Each cylinder is fitted with two ingress valves and one egress valve at each end. The valves with thin cages are of gun metal, and the screws for them are of steel. The injectors placed on the cylinders for pulverising the water are of gun metal; there are four of them to each cylinder. To ensure uninterrupted service, the friction surfaces have been made large in area, and the oil-cups very large. The piston rods, connecting rods, and cotters are of steel. The holding-down and other bolts are of iron. With a minimum force of 325 horse-power

at the shaft, 216 cubic feet of compressed air should be produced per minute.

AVERAGE MONTHLY RESULTS OF MECHANICAL PERFORATION IN THE ADVANCED GALLERIES DURING THE THREE MONTHS ENDING SEPTEMBER 30, 1878.

Elements for Comparison.		North End.	South End.	Total.
Machines employed		Ferroux	McKean	—
Average cross section of gallery	sq. yards	8·13	7·48	7·80
Monthly advance	yards	115·6	154·1	269·7
Average advance per diem	,,	3·76	5·43	9·19
Maximum ,, in one day	,,	5·72	7·00	7·00
Number of shifts	shifts	81	107	188
		h. m.	h. m.	h. m.
,, hours at work	time	728 40	678 23	1,407 3
Time lost	,,	9 40	55 40	65 20
,, to drill the headings	,,	389 10	332 20	721 30
,, to blast and clear away	,,	332 50	346 30	679 20
		m.	m.	m.
Average time to drill one yard of hole	,,	41·5	33·3	37·4
		h. m.	h. m.	h. m.
Average time to drill the heading for one attack	time	5 11	3 10	4 10
Average time to blast and clear away	,,	4 9	3 15	3 42
,, from one attack to the next	,,	9 20	6 25	7 53
Total number of holes made	holes	1,679	1,852	3,531
Average number per attack or shift	,,	20·7	17·39	19·04
Total length of all the holes	yards	2069·3	2,671	4740·3
Average length per attack	,,	30·29	25·01	27·65
,, ,, of one hole	,,	1·46	1·43	1·44
Length of all the attacks	,,	119·3	162·7	282·0
Advance obtained	,,	115·6	154·1	269·7
,, ,, per attack	,,	1·42	1·44	1·43
Length pierced per attack, but not utilised	,,	0·96	1·41	1·19
,, ,, hole	ins.	1·58	3·03	2·30
Number of shifts of machines employed		324	496	820
Average number of machines placed on the carriage		4	4·62	4·31
Total number of machines sent for repair		25	47	72
Proportion per cent.	per cent.	8·15	9·37	8·86
Total number of jumpers sent for repair		5,993	5,085	11,078
Average number of jumpers per hole		3·63	2·80	3·22
Minimum pressure of compressed air at the front	atmospheres	3·20	3·11	3·11
Average pressure of compressed air at the front	atmospheres	3·62	3·51	3·56
Maximum pressure of compressed air at the front	atmospheres	4·03	4·55	4·55
Average temperature of air whilst machines were at work	Fahr.	74·7°	77·2°	76·0°
Average temperature of air whilst clearing away	Fahr.	79·7°	84·2°	82·0°

The average daily consumption of dynamite for blasting purposes during three months ending September 30, 1878, was as follows:—

—	North.	South.	Total.
In the advanced gallery . . lbs.	171·6	200·6	372·2
„ other parts of the tunnel . .	330·0	352·4	682·4
Total consumed per day .	501·6	553·0	1054·6

For the advanced galleries, which progressed at the average rates of 3·76 and 5·43 yards per day, north and south combined, the quantities of dynamite consumed were at the rates of 46 lbs. and 39 lbs. per lineal yard.

The quantity of rock excavated at the north end during the month of November 1878 amounted to 7,282 cubic yards; of broken rock 7,560 wagon-loads were removed, averaging 252 loads a day. The maximum number of loads removed on one day was 332. The total space in the tunnel at November 30, 1878, amounted to 269,363 cubic yards. At the end of the month 314 cubic yards of ballast had been laid.

The total length of the air-conduit at the north side, at the end of November, amounted to 9,320 yards, consisting of 6,841 yards of main pipe and 2,479 yards of branches. Early in 1877, the enlarging and relaying of the pipes was proceeded with at both ends, in order to augment the pressure at the front, which had dwindled down to from 2 to $2\frac{1}{2}$ atmospheres. Portions of the $2\frac{3}{8}$-inch pipes were replaced by others 8 inches in diameter. On November 30, 1878, the pipes were of the following dimensions: 52·3 per cent. of 8-inch pipe, 9·8 per cent. of 6-inch pipe, 11·3 per cent. of 4-inch pipe, 26·4 per cent. of $2\frac{3}{8}$-inch pipe, and 0·2 per cent. of tube $1\frac{1}{5}$ inch in diameter. The total void capacity of the tunnel was 285,240 cubic yards, and the total quantity of compressed air introduced daily into the tunnel averaged 175,690 cubic yards at atmospheric pressure. Of this, one-eighth was consumed by the air locomotives, mostly within the tunnel, but partly outside it. The absolute pressure of air was—

	Atmospheres.	Atmospheres.
Average	7·15 at the entrance	4·33 at the front
Maximum	7·50 „ „	7·00 „
Minimum	6·75 „ „	3·66 „

At the south end, 415 trains, comprising 9,310 loaded wagons, passed out of the tunnel during November 1878, making an average per day of 13·83 trains and 310 wagons. Air pipes, 8 inches in diameter, were laid continuously for a length of 5,151 yards. The total space in the tunnel amounted to 259,574 cubic yards, of which the advanced gallery comprised 19 per cent. The volume of air at atmospheric pressure introduced into the tunnel in November averaged 119,770 cubic yards per day, equal to only 46 per cent. of the total void capacity. The deficiency of the supply was caused by an accident affecting the water for working the compressors. The absolute pressure averaged only 3·32 atmospheres at the entrance and 2·78 atmospheres at the front.

Locomotive Power.—There were three compressed air locomotives employed at each end for moving empty and loaded wagons. In general arrangement these are similar to the engines described in the first article on this tunnel, which appeared in the earlier edition (Chapter XXIV.). The engines are provided with M. McKarski's hot water reservoir, and with M. Ribourt's automatic governor, by which steam, air, or other gas is wire-drawn from a higher pressure, that may be variable, to any constant pressure in the cylinder. The gauge of the track is one metre. The engine is placed on four coupled wheels, 30 inches in diameter and 4 feet 1 inch apart between centres. The cylinders are 7·88 inches in diameter, with a stroke of 14 inches. The reservoir is cylindrical, 5 feet 7 inches in diameter and 11 feet 8 inches long, having a capacity of about 260 cubic feet. The reservoir is charged with an air of 14 atmospheres, and is wire-drawn, so as to give a pressure of 4 atmospheres in the cylinders, or 45 lbs. per square inch effective pressure. The weight of the engine is about 7½ tons.

Labour Employed.—The number of men employed during the three months ending September 30, 1878, was—

	Average Number.	Maximum Number.
North end	1,264	1,510
South end	1,819	2,025
Total employed	3,083	3,535

In September 1878 the men were thus distributed:—

—	Within the Tunnel.	Outside.	Total.
North end	918	341	1,259
South end	1,199	582	1,781
Total employed	2,117	923	3,040

In September 1878 thirty-eight horses were at work.

Temperature in the Tunnel.—From the results of observations recorded in the monthly reports to the end of August 1878, it appears that the temperature within the tunnel at the north end rose gradually at the front during 1877 and 1878, and that there was a gradual elevation of temperature at the south end from the beginning of 1875; also that the temperature at the south end was generally higher than at the north end during the later years. The difference may possibly be ascribed to the greater depth of the mountain over the southern portion of the tunnel. At the north end, on December 4, 1877, a thermometer suspended at the front indicated 77° Fahrenheit. The entrance of compressed air having been stopped at this time, in order to carry out some repairs, and the front being perfectly free, the temperature fell in the course of fifty-five minutes to 75·33° Fahrenheit; and for the next two hours it showed an average temperature of 75·29° Fahrenheit, which approaches closely to the observed temperature of the rock at a distance of 5,431 yards from the mouth of the tunnel. The vertical depth of the mass of the rock over the advanced gallery, at the point where the thermometer was placed, was (2,303 above the sea – 1,246) 1,057 yards. The estimated augmentation of temperature due to the depth is given as 36·9° Fahrenheit, and adding this to the

average surface temperature of the soil at the given elevation—namely, 37·72° Fahrenheit—the sum 74·62° Fahrenheit is the temperature due to the depth, which is but slightly less than the observed temperature above noted.

By the end of 1878, the high temperature at the south front, which had reached 84° Fahrenheit, was very inconvenient to those engaged in the heading. Whilst the machines were in action they were enveloped in mist; and the difference between the temperature in the immediate neighbourhood of the compressed air cocks, and the temperature at the distance of a few paces, was unavoidably injurious to health. The horses in particular suffered much by the great heat.

On October 29, at a distance of 4,943 yards from the south entrance, the average temperature at the front was 84·6° Fahr., the temperature of spring water being 86° Fahr., whilst that of the rock was 82·3° Fahr.

Loss of Life, &c.—The history of the St. Gothard Tunnel would be incomplete without reference to a melancholy event which occurred in July 1879. Allusion is made to the death of M. Louis Favre, the engineer in whose charge the construction of the tunnel had been since its commencement in 1872, and to whose untiring energy, experience, and fertility of resource the successful conduct of this great work was largely due. The unfortunate gentleman was seized with an apoplectic fit whilst making an inspection of the tunnel, from which he did not recover. It may here be added that 177 lives were unfortunately lost during the ten years which the construction of the tunnel occupied.

This deplorable mortality was mainly caused by the unhealthy conditions under which the labour was carried on, assisted, doubtless, by the habit, so general amongst Continental workmen, of working all seven days of the week. At the end of 1880, the reports as to the sufferings of the men employed were so alarming that a committee of medical men was appointed to enquire into, and report on, the condition of affairs. It was found that there was no epidemic disease amongst the men, but that chest complaints and especially anæmia, or deficiency of red particles in the blood, were prevalent. The air was found to be loaded with aqueous matter, and to carry a large proportion of carbonic acid, which was

rendered additionally impure by the exhalations from stagnant pools of water, and from the bodies of those engaged in the tunnel, and by the smoke of the lamps employed for lighting. By the end of March 1880, there had been 122 deaths amongst the employés, and of these only 47 were the results of accident. 90 men were dismissed in the first three months of 1891 who were found to be suffering from anæmia.

Junction of the Headings.—The headings were successfully pushed forward until the early part of 1880, when, in anticipation of the approaching junction of the two headings, telegraphic communication had been established between the northern and southern ends of the tunnel. In the last week of February 1880, the chief miner at the south end probed the front from time to time with a 10-foot jumper rod, making a 3½-inch hole, until on Saturday evening, February 28, the rod protruded into empty space, and communication, oral and written, could be made with the miners at the north end. The holes which were drilled for charges were now limited from 2½ to 4 feet in length, and charged at the south end only. When the partition wall was reduced to a thickness of 4½ feet the four central holes only were charged at the south end, and seven others were formed, surrounding the central holes within a radius of 26 inches. By the explosion which followed, a large funnel-shaped opening was made in the wall, five feet in diameter at the south side, and a little more than half that diameter at the north end. A passage for the men was thus opened on February 29, 1880, a little before noon.

The length of the tunnel had been determined to be 16,295 yards, inclusive of 158 yards which was the length of the curvilinear portion at the south end. In determining the vertical plane of the tunnel, the method of surveying from a single observatory on a mountain half-way, practised at Mont Cenis or Mont Fréjus, could not be adopted at St. Gothard, as the Castelhorn, which was situated midway between the ends of the tunnel, had two summits nearly of the same height. One of these was inaccessible and marked the summits which were further off. It was necessary, therefore, to connect the ends of the tunnel by triangulation, a work which was performed by Otto Gelpke in 1869. He laid out eleven triangles, in connection

with the Federal surveys, and with a base 4,757½ feet long measured in the plain of Andermatt, under which the tunnel was to pass. For a tunnel 9¼ miles long, an error of five seconds at each side would have incurred a deviation of 16 inches at the middle of the tunnel.

The deviations between the two parts of the tunnel at the connecting point did not exceed 4 inches vertically, and between 6 and 8 inches horizontally. For the total length of the tunnel, there is a difference of 25 feet between the length as determined trigonometrically and the sum of the direct measurements made in the tunnel by means of rods or of steel bands.

At Mont Fréjus, it may be noted, the difference of length amounted to 44½ feet, and the lateral deviation to about 16 inches.

Comparing the Mont Cenis Tunnel with the St. Gothard Tunnel, 13 years 1 month, and 7 years 5 months, were respectively occupied in piercing the ground for the advanced galleries, which progressed at the rates of 78 yards and 183 yards per month. The greater rate of progress made in the piercing of the St. Gothard was due, 1st, to the system of excavation by a top heading adopted by M. Favre, as against the bottom heading adopted in Mont Cenis; 2nd, to the more effective employment of the hydraulic power at command; 3rd, to the use of improved high-speed air compressors, with finely divided water for keeping the apparatus at a moderate temperature; 4th, to the use of very efficient rock drills and drill carriages; 5th, to the use of dynamite instead of compressed powder; 6th, to the employment of locomotives worked by compressed air of twelve and fourteen atmospheres.

The bell ventilators which were erected by M. Favre at each end of the St. Gothard tunnel remained unemployed.

In June 1880 a very serious difficulty was encountered, owing to the falling in of a portion of over 100 yards of the work which passed through a bed of white porous stone; the subsidence was so serious that it defied every effort on the part of the engineers to repair the repeated settlement of the roof. The formation at this section consists of strata of gypsum and calcareous schists, which absorb moisture freely, then swell, and disintegrate.

So as to prevent the tunnel from sinking in, a granite wall 6 feet in thickness was built, but this too was found to be giving way. In order, therefore, to surmount the difficulty, the dangerous portion of the tunnel was eventually enlarged and lined with granite walls, arching and invert, being of great thickness. The lining, however, is not continuous, but is built in separate lengths of about 12 feet, so that any settlement which might follow would affect only a short distance of the work. The two end sections were built first, so as to secure a firm abutment against the sound portion of the tunnel, and from these, two successive lengths were advanced on each side towards the centre of the insecure portion. The masonry at the centre of the arch is 4 feet 8 inches thick; at the spring 8 feet 3 inches, and at the invert about 2 feet thick. The execution of this portion of the work was not only slow in itself, but it greatly retarded the execution of the portion beyond, as its reconstruction embarrassed the regular progress of the removal of the soil.

On the evening of December 23, 1881, a locomotive passed through the tunnel for the first time on the permanent rails, and on January 1, 1882, the Göschenen-Airolo line was provisionally opened.

Before the heading was completed, the material excavated was removed by means of the compressed air locomotives, but after its completion on February 27, 1880, ordinary engines were used. Twelve trains traversed the tunnel daily, and in addition to the smoke from the engines that produced by 860 oil lamps and 360 kilogrammes of dynamite had to be disposed of. It was found, however, that the natural draught through the tunnel satisfactorily effected this, the only inconvenience experienced by the men engaged on the work being that caused by the heat.

The northern end of the tunnel is 3,638 feet and the southern end 3,756 feet above sea level. To overcome the sudden rise from the level of the St. Gothard Railway proper to the mouths of the tunnel spiral tunnels of approach had to be constructed, which run above one another on a radius of 15 chains and a gradient of 1 in 43·5. There are three of these spiral tunnels at the north, and four at the south end of the great tunnel. The line rises to a summit level within the tunnel 190 yards long. It is

47·46 yards above Göschenen, and 8·09 yards above Airolo, the northern gradient being at the rate of 1 in 172, and the southern at the rate of 1 in 1,000.

An interval of twenty-two months elapsed between the junction of the headings in the St. Gothard Tunnel and its completion, as compared with nine months in the case of the Mont Cenis Tunnel. The longer interval is probably due to the fact that the enlargement work could not follow the headings so closely in the former as in the last-mentioned tunnel. In the St. Gothard these headings were driven along the top; in the Mont Cenis they were at the bottom of the tunnel.

The cost of the St. Gothard Tunnel was approximately 2,327,000*l*., being at the rate of 142*l*. per lineal yard. In spite, therefore, of its greater length the cost was somewhat less than four-fifths of that of the Mont Cenis Tunnel, and only two-thirds of the cost per yard of the latter. The cost of the Arlberg Tunnel averaged only about 85*l*. per yard, and it is anticipated that the cost of the Simplon Tunnel will be lower still. This reduction, as previously suggested, is probably due largely to the greater rapidity in the execution of the work, consequent on the improvements introduced into the machinery used.

WIDENING OF THE ST. GOTHARD TUNNEL.

The subsequent widening of the tunnel in 1889 presented serious difficulties, as but little room had been left between the existing line and the rock which had to be removed. Figs. 1, 2, and 3, Plate XX., show how the different types of the tunnel section were left when first constructed. The choice of the type of tunnel depended upon the character of the rock to be excavated.

Where the rock was not considered to be firm enough, a lining of masonry was ordinarily constructed, with a space between it and the rock. This space was filled with dry rubble, to allow the water which percolated through the fissures of the rock drain down to the weep-holes at the rail level, thus almost entirely preventing the destructive action of the water upon the masonry. Work in the tunnel was carried on principally at

PLATE XX.

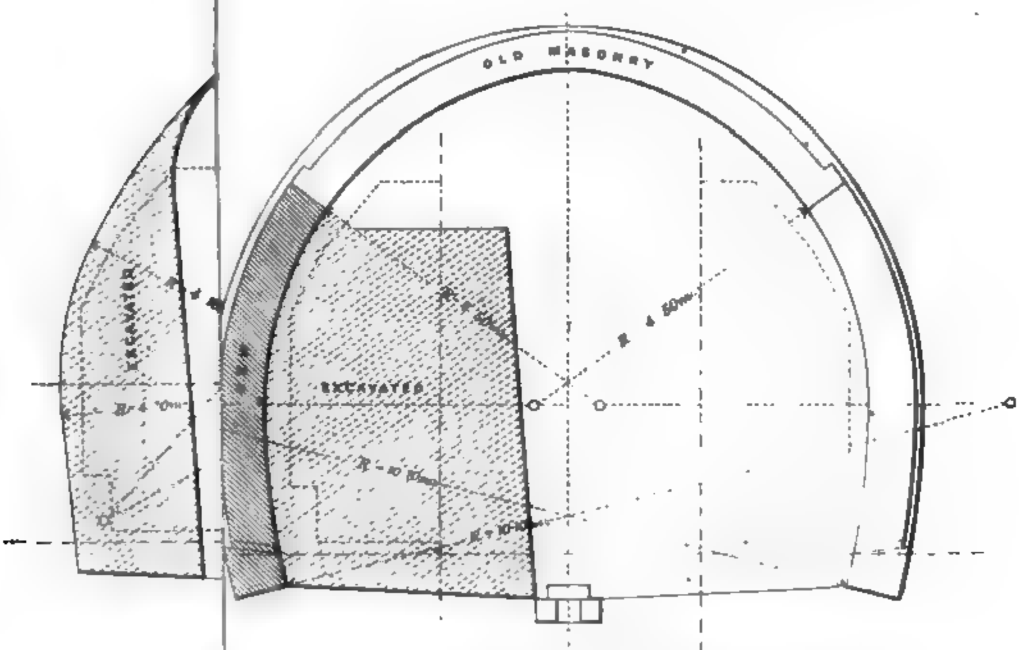


FIG. 1.—ST. GOT

FIG. 3. ST. GOTHARD TUNNEL. TYPE OF CONSTRUCTION NO. 3.
(SCALE = $\frac{1}{100}$.)

[Between pages 362 and 363.

night, when the traffic was lightest; although, even then, the smoke remaining from the engines, particularly in the helicoidal, or spiral, tunnels previously referred to, delayed the work considerably. The explosives used, both for the tunnels and the open lines, were blasting powder, gelatine dynamite, and Favier dynamite. The last-mentioned explosive is less dangerous to handle than dynamite; but the exercise of great care is necessary in boring the holes.

Of the thirty tunnels on the approaches, only four, of the aggregate length of 312 yards, were originally constructed for a double track; one of 47 yards in length was not widened, as the second line was taken outside the mountain. The remaining twenty-five tunnels (12,823 yards) were widened, and were partly lined with masonry. The material, excavated entirely by blasting, amounted to 240,000 cubic yards, and the masonry lining amounted to 38,000 cubic yards. After completing the necessary excavation, the masonry for the widening of the abutments and piers and the lengthening of arches was built in the usual way, with or without staging, according to circumstances. Between the old and new masonry all bond was avoided. The surface of the old masonry where it had to be joined by new work was dressed off, the surface of the original work being, as a rule, rock-faced granite, thus permitting the new masonry to settle without causing cracks, through its hanging on to the rough sides of the old masonry. Several of the abutments and piers widened are very high; the Kerstelenbach pier, for instance, is 164 feet high, and shows no opening between the old and new masonry.

The girders were constructed to match those already existing. The larger spans, from 100 to 246 feet, are of the quadruple, triangular system, with stiff verticals. There is, as a rule, plenty of room below rail level, and most of the bridges carry the road on the top of the girders.

[An article dealing with the ventilation of the St. Gothard Tunnel will be found under the chapter on 'Ventilation of Tunnels;' see pp. 534–539].

CHAPTER XXVIII.

TUNNELLING IN HARD ROCK (CONTINUED)—
TUNNELS ON DORE AND CHINLEY RAILWAY (MIDLAND SYSTEM).

THE Bill for the Dore and Chinley line was first introduced into Parliament in 1884, with the support of the Midland Company, and sanction was obtained for the incorporation of the Dore and Chinley Railway Company and for the construction of the line. On the failure of that company, in 1887, to raise the necessary capital, the Midland Company obtained sanction in 1888 for the acquisition of its powers, and the works were commenced forthwith. Two contracts were let; the first 10½ miles being taken by Mr. Thomas Oliver, of Horsham, and the remainder by Mr. J. P. Edwards, of Chester. The engineers were Messrs. Parry & Storey, M.M.Inst.C.E., of Nottingham and Derby, and the works proved to be of an exceptionally heavy character. There are three tunnels: the Totley Tunnel, over 3½ miles in length; the Cowburn Tunnel, over 2 miles long; and a short tunnel of over 90 yards on the Dore South Junction Curve. There are also two large viaducts, one at Hathersage, 130 yards in length, and the Milton Viaduct, 250 yards long and 105 feet high, forming the South Junction Curve at Chinley. There is also a heavy road and river diversion in the Edale Valley, and a 100-foot span bridge over the Derwent at Bamford. There are five stations—viz. Grindleford, Hathersage, Bamford, Hope (for Castleton), and Edale.

THE TOTLEY TUNNEL.

The Totley Tunnel passes for the greater part of its length under moorland, which rises upwards of 1,250 feet above sea level and is 730

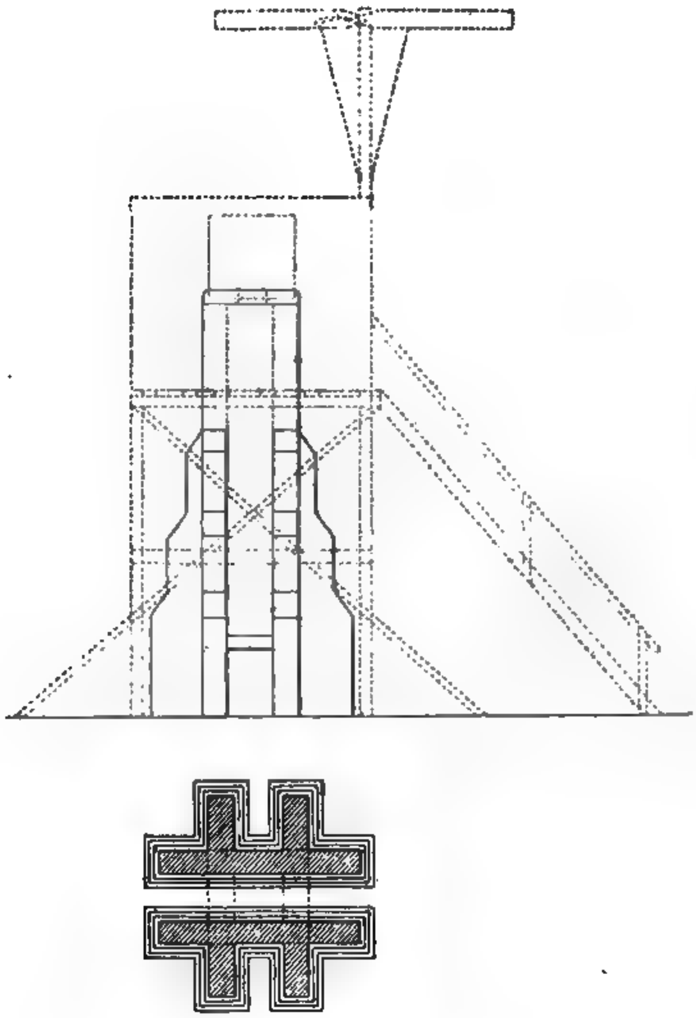
feet above the level of the rails. It connects the valleys of the Sheaf and the Derwent; lies nearly due east and west; and, with the exception of 100 yards at its western end, is straight throughout, the curved portion being to a radius of 40 chains and deflecting northwards. Approached from Dore by a long cutting through the bottom of the valley, on a rising gradient of 1 in 100 which extends for a quarter of a mile into the tunnel, the subsequent gradients are 1 in 176, followed by 1 in 150 to the summit level, ten chains in length. The line then falls on a gradient of 1 in 1,000, and emerges abruptly from the precipitous face of the hill 130 feet above the bed of the river, the difference in the level between the two ends of the tunnel being 77 feet.

The Alignment above ground.—The greatest precautions were taken to secure the accurate setting out of the centre line. As the longitudinal section (fig. 1, Plate XXI.) shows, the profile was favourable to this work, distinct changes in the surface taking place at convenient distances, and high ground beyond each extremity of the tunnel accommodated terminal stations, which could be seen from the summit observatory; there was no need to reverse the transit instrument except at that point. The line having been fixed with as much accuracy as could be obtained with a 6-inch theodolite, brick observatories were built at the extreme stations (Bradway and Sir William), and at each end of the changes of the ground surface over the tunnel. In addition to these, an observatory (No. 3 west) was also built beyond the entrance at Padley, at a level to command the heading on the 1 in 1,000 gradient; and a station was fixed at the foot of the hill beyond (No. 4 west) to enable these two points to be seen from within the heading whenever necessary.

The observatories (figs. 2 and 3) were built hollow, of brickwork in cement, and capped with stone. A large flat cast-iron plate, having a hole 6 inches wide in the centre, was let into the cap and run with cement; upon this the transit instrument rested. A brass scale 1½ inches wide, divided into inches and twentieths of an inch, was fixed across this central hole in the plate, and a plumb line from the centre of the instrument could then be let down from the hole in the plate to touch the side of the scale. The

transit instrument was of the fixed type, with a 3-inch object glass and a 30-inch telescope.

In order to enable it to be used with facility at different observatories, as required, an extra cast-iron base was added, resting upon three levelling screws, and upon it the ordinary standard rested. The latter was pivoted on one end, and was secured between two slow-motion adjusting screws at the other. A hole 3 inches in diameter was made in this baseplate to allow the plumbing hook to pass freely through it from the bottom of the standard to which it was attached. The extra baseplate enabled the instruments to be levelled with accuracy, and also provided a slow horizontal movement similar to that of an ordinary theodolite.



FIGS. 2 AND 3.

In setting out the line, two points in that set by the small instrument were taken as fixed—viz. the summit and No. 1 west (fig. 1, Plate XXI.), and from the summit observatory the line was set upon the extreme

observatories east and west and upon No. 1 east. The instrument was then removed to No. 1 west, and, with the Sir William observatory as a fixed point, the line was set on No. 2 west. The instrument was then removed to No. 2 west, and the line was in the same way set upon No. 3 west, and similarly upon Nos. 2, 3, and 4 east. The instrument was subsequently set up at Bradway and Sir William observatories, and the centre lines of No. 4 east and No. 3 west were checked. No. 4 west was then set from No. 3 west, and checked from No. 2 west, and the external line was complete.

The objects found most easily distinguishable for lighting upon in the open were: (1) A board with a 3-inch central white line painted upon a black ground fitted with a plummet and fixed by guy ropes. A large white calico screen, which was inclined towards the sun, was fixed behind the board, and a few feet away so as to avoid shadow. This arrangement was used at the terminal stations, which were each more than 3 miles from the summit, but could only be clearly distinguishable at that distance so long as the sun was in front of the screen. (2) An iron tripod 6 feet high (fig. 4), with adjustable screwed legs, from which was suspended a heavily weighted fine steel wire. On this wire was centred a 1-inch blackened tube, 5 feet long. This instrument was used against the sky, as at the summit observatory, the adjustment screws being used to bring the fine wire exactly to the right division on the scale. (3) A broad-arrow board, 2 feet by 1 foot 6 inches, faced with white cardboard on which was drawn a broad arrow with varying widths of shaft. This was levelled with a spirit level and supported from the back with light iron stays, and was used for short distances.

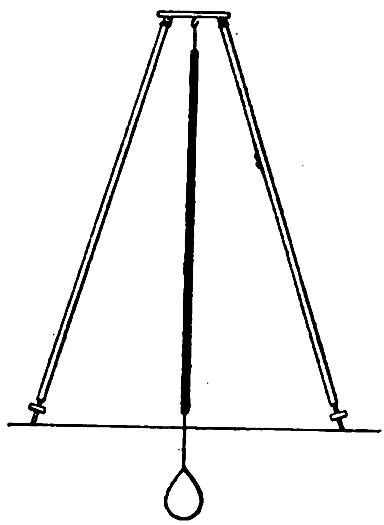


FIG. 4.

For transferring the centre line down the shafts the apparatus shown in figs. 5 and 6 was used. It consisted of a winding drum carrying the

wire, mounted upon an iron frame with a ratchet and pawl to secure it in any position. The wire passed over an adjusting screw, and was brought into line by turning the screw in either direction as required.

Great difficulty was experienced at the outset in finding favourable weather for fixing the line upon the terminal stations, as it was essential that

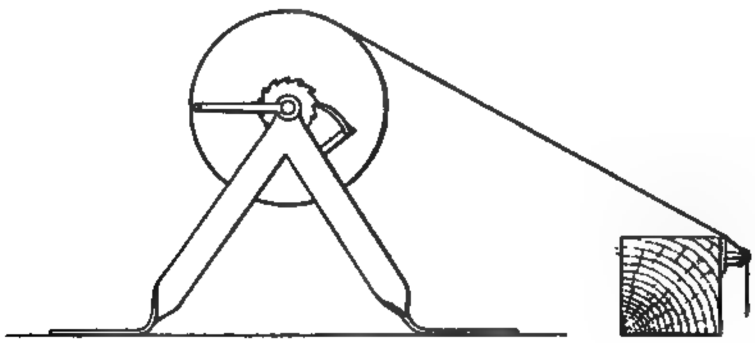


Fig. 5.

the atmosphere should be clear, sufficiently cool to prevent aberrations due to heat, and yet still enough for the observatory to be free from vibration. It was also necessary that the time of day should be such that the sun would illuminate the front of both screens behind the objects to be

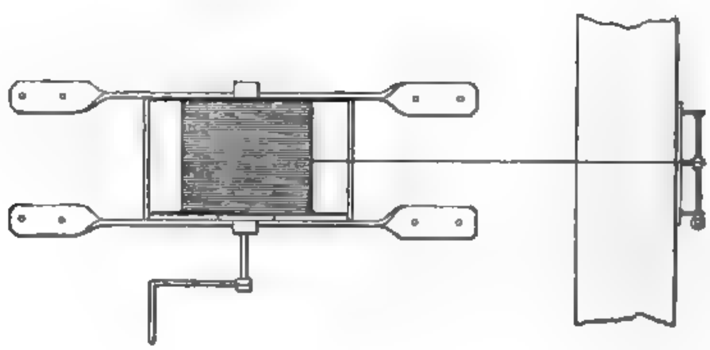


Fig. 6.

sighted. The only time when the weather answered all these requirements were rare occasions in the spring and autumn between the abatement of a high wind and a fall of rain; and as these could not be predicted beforehand and a day's preparations were necessary, much time was wasted. The greatest difficulty was found in sighting across the Derwent valley

westwards, but excellent opportunities for sighting east were always obtainable at sunset after a warm summer's day.

The Alignment underground.—After the centre line had been fixed upon the observatories at the surface, the positions of the four shafts at Totley were set out from them; and when the shafts had been sunk, the centre line for the headings was transferred below, in the ordinary way, by weighted wires suspended from the top, the lines being produced underground by a small theodolite until the headings met between the shafts. The brick lining was then proceeded with, and the centre line was again carefully transferred below upon byats fixed securely into the brickwork at No. 4 shaft and at B shaft (fig. 1, Plate XXI.). With this bearing, the line was produced by the large transit instrument westwards into the heading as required. At Padley the line was produced into the heading direct from the observatory (No. 3 west). When used underground, the large transit instrument rested upon a balk of timber, which was supported at each end so as to clear the temporary road. The extreme range of the instrument below ground, when the air was clear, was about three-quarters of a mile; but as the headings advanced, not more than ten or fifteen chains could be seen under the most favourable circumstances, and the small instrument was then used in preference. The line was marked with a file upon iron dogs driven into the byats, or head trees, in the usual way, and to avoid instrumental errors the line was set out twice, the telescope being turned over transversely in the bearings between the operations. The mean of the two results was the centre line adopted.

The objects used for sighting upon underground were: (1) for long distances, a large circular-wick oil lamp of 40-candle power, fitted into a circular wrought-iron frame, which was suspended by a wire; and (2) for shorter distances, for use with the smaller instrument, a carriage candle fixed on a weighted frame and suspended in the same way.

For signalling long distances with the large instrument, an electrical signalling apparatus was employed (figs. 7 and 8). It consisted of two similar instruments, in each of which a 7-inch single-beat bell was mounted, with a battery enclosed beneath, together with a three-

quarter mile single gutta-percha covered cable wound on a drum, and mounted on a portable frame. The cable was thus readily paid out from the trolly on which the instruments were conveyed every time it was used, and the return was made to earth through a galvanised-iron plate temporarily sunk into the ground. With this apparatus messages could be sent in either direction, and to prevent misunder-

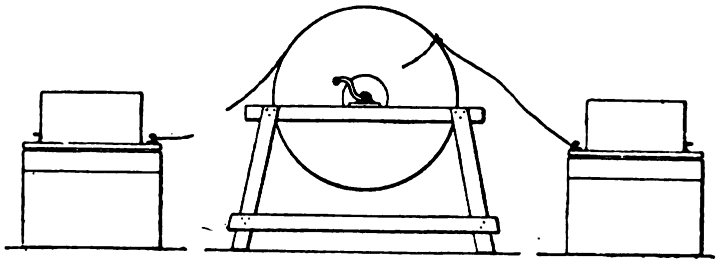


FIG. 7.

standing all signals were repeated by the receiver, and any error in transmission could then be corrected by the transmitter. The advantages of electrical signalling were incalculable, for, besides overcoming the difficulty of setting out at such a long range in a narrow heading, it saved that straining of the eye for signals on the part of the operator which is so trying under ordinary circumstances, and thus favoured better work. For signalling short distances with the small instrument, a red, white, and

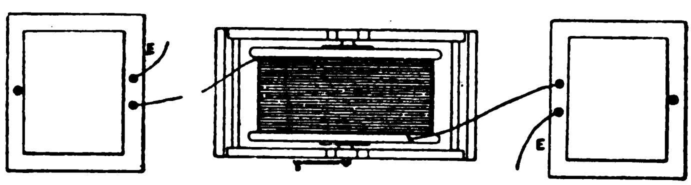


FIG. 8.

green hand-lamp was used. When the headings met, the difference between the centre lines of the two headings was found to be $4\frac{1}{2}$ inches, and the difference between the levels was $2\frac{1}{4}$ inches.

Sinking the Shafts.—Although powers were granted by the Act to sink a ventilating shaft at the summit level of the tunnel, it was not considered advisable, for several reasons, to construct it at first. Four permanent shafts

were sunk at the commencement, all of which are within three-quarters of a mile of the Totley entrance. To facilitate the driving of the headings and the lining of the tunnel, they were not lined with brickwork until some time after they had been sunk, and when they were no longer necessary for haulage purposes.

Three temporary shafts, A, B, and C (fig. 1, Plate XXI.), were sunk in addition, A being at the east entrance and B and C between that point and No. 1 shaft. Shaft A, commenced on September 24, 1888, was used for a pumping station until the cutting had been excavated and the drainage could flow out naturally. It was sunk wholly in shale. Water was met with at a depth of only 8 feet, increasing in quantity until the full depth was attained in November 1888, when the discharge amounted to 10,000 gallons per hour. Shafts B and C were commenced on November 28, 1888, and January 3, 1889, respectively. They were sunk entirely in dry shale, which had been drained by A shaft.

The permanent shaft No. 1 was commenced on September 11, 1888. The material traversed was dry shale, with one 4-foot bed of rock, which brought in a large quantity of water. The full depth of 87 feet was reached on October 30, 1888. Shaft No. 2 was commenced on September 17, 1888, in dry shale. At 20 feet, thin beds of coal and fireclay were cut through, then shale again as far as 80 feet, when more beds of coal, ganister, fireclay, and rock were found, with a large quantity of water. These were succeeded by shale and another 6-foot bed of rock, and finally shale again to the full depth of 141 feet, which was reached on December 1, 1888. Shaft No. 3 was commenced on September 24, 1888, the material passed through in the first 160 feet being shale, with several beds of rock a few feet in thickness, but without water —the same beds having been previously intersected and drained by shafts Nos. 1 and 2. Then followed rock with a considerable quantity of water, which continued to the full depth of 235 feet, reached on March 27, 1889. The quantity of water discharged was 8,000 gallons per hour. Soon after the shaft had been sunk the pump became drowned, and nothing further was attempted until the heading from No. 2 shaft was driven so far forward as

to liberate the water. Shaft No. 4 was commenced on September 20, 1888, the first 50 feet traversing dry shale; then a bed of coal and rock was reached, with large quantities of water; and this was succeeded at 80 feet by beds of shale and rock, the rock in each case yielding more water. On January 30, 1889, a depth of 180 feet had been sunk, the quantity of water then discharged being 15,000 gallons per hour. It was decided to increase the size of this shaft from 10 to 15 feet diameter, so as to accommodate a pair of cages for winding gear. Further sinking was therefore stopped, and the widening of the shaft was commenced from the surface on February 4, 1889. By April 9, 1889, the widening had been carried down to where the sinking had been suspended, and the enlarged shaft was then continued. At 185 feet, a 15-foot bed of rock was passed through, followed, after 5 feet of shale, by another bed 18 feet thick, the quantity of water to be raised by the pumps being largely increased. Shale was then passed through until the full depth of 280 feet had been sunk on June 19, 1889. The quantity of water discharged by the pumps finally reached 26,000 gallons per hour.

The Headings.—The size of the heading throughout was 10 feet by 9 feet clear of timber, large enough to take a fully loaded wagon, and it was driven at the formation level or thereabouts. A commencement was made at Padley on September 27, 1888, the first 530 yards being driven by hand power only. After penetrating a few yards of gravel, black shale was reached, accompanied by water from the roof, which gradually increased in quantity as the heading proceeded, and was carried off by an open grip. In June 1889, the first break-up was made at this end, and, as much difficulty was found in excavating the foundations of the side walls, owing to the water finding its way from the grip through the fissures in the shale, it became desirable to carry off the water at a lower level than the foundations. The heading was therefore stopped from June to August 1889, whilst a 12-inch drain was laid from the open end below the invert level. When the driving of the heading was resumed, it was found that sinking the drain at so great a depth hindered the work, and the contractor was allowed to run the heading down hill, and to proceed at a

level 4 feet lower than the formation, in order to save time and labour in excavating the drain. This was done at 400 yards from the entrance.

At Totley the headings were started as soon as the shafts reached their full depths, and were driven in both directions from each shaft until they met. From shaft A the heading was entirely in the shale, and yielded a large quantity of water. From shaft B eastwards dry shale only was pierced, which had been drained from shaft A. Westwards the black shale terminated in a fault, where a large spring was tapped which flooded the headings for four days, the pump at shaft A, although discharging 26,000 gallons per hour, being temporarily unable to deal with it. The water, however, diminished and work was then resumed, the total discharge afterwards was reduced to 12,000 gallons per hour. After passing the fault, beds of coal, fireclay, and rock were passed through. From shaft C only a few yards were driven in dry ground before the headings met in both directions.

From No. 1 shaft, eastwards, the heading was entirely in dry black shale. Westwards, 100 yards were driven in the shale, when another series of beds of coal, fireclay, and rock were cut through, the latter formation yielding much water, the quantity discharged amounting to 25,000 gallons per hour. In ten days' time this quantity had diminished by one-half. After leaving the rock, black shale was again reached, and it continued until the heading met that from No. 2 shaft. From No. 2 shaft eastwards black shale, with a bed of rock, was passed through, and westwards a similar bed of rock was pierced, the quantity of water from both amounting to 10,000 gallons per hour. After passing through more shale and a bed of coal, rock was reached. On May 26, 1889, No. 3 shaft was reached, and the water in it was liberated. Shale, coal, fireclay, and rock were successively passed, the rock bringing in more water. On September 21, 1889, the heading met that from No. 4 shaft. From No. 4 shaft only a few yards were driven each way, owing to a stoppage of the pump, followed by a total disablement, the pump being drowned.

From February 15 to September 4, 1889, at 1,167 yards, all the water discharged into the headings was lifted at shaft A, the maximum quantity

reaching 2,250,000 gallons per day. The same trouble was now found with the water in the foundation of the side walls, as had been previously experienced at Padley, and a 12-inch pipe was therefore laid from the entrance to drain them, which, by January 1890, was carried as far as No. 4 shaft, an open grip sufficing beyond that point. The quantity of water encountered was, however, so great that the 12-inch pipes proved insufficient to deal with it, and by July 3 the driving had to be suspended. The 12-inch pipes—which had been found very difficult to lay properly through the uneven beds of rock and hard shale, and much more difficult to keep free from silt when laid—were taken up, and a grip 2 feet 6 inches square was cut along the bottom of the heading instead and covered with 3-inch planking. At 1,560 yards, a wall 4 feet 6 inches thick, having a camber of 6 inches horizontally, was built across the heading in brickwork in cement. Seven 4-inch wrought-iron pipes, one of which was furnished with a pressure gauge, were built in through the wall, having plug-cocks fitted at their outer ends, which remained open until the brickwork had set. The cocks were closed, and the work of excavating for the drain pushed forward. The pressure rose until, in ten days, it had attained 127 lb. to the square inch. Meanwhile, the leakage through the fissures in the rock was more than a 4-inch pipe, which had been laid down in the heading, would take, and a second wall 18 inches in thickness was built 71 yards below the first one, to increase the discharge of the pipe by increasing the head of water. The covered drain was then carried as far as the outer wall, which was removed. The pressure on the inner wall was tested, and was found to have risen to 155 lb. per square inch. The drain was then carried forward until, by August 11, it had reached the inner wall. This was then removed, and driving was resumed after a stoppage of six weeks. More rock, with water, was passed through, and finally, at 2,070 yards, dry black shale was again reached, which continued as far as the junction at 3,700 yards.

Similar difficulties occurred in the heading at Padley. It had advanced on November 16, 1891, to 1,880 yards, when an inrush of water took place at the face which dwarfed everything previously met with. A round of holes

had been drilled in the rock, and were about to be charged, when a plug of soft earth was forced out of a fissure in the roof and about a yard from the face, and a stream of water issued, which rapidly increased from a few square inches in area to the full width of the heading and two feet across. Tons of sand, silt, and stones were hurled down the fissure, and were carried far down the heading by the torrent. A natural reservoir was discharging itself, and the water, rushing down the heading, was impounded where the level dipped, and eventually cut off all access to the face. It was decided to proceed at once with the permanent drain from the entrance to where the lining was completed, and to substitute a covered grip for the 12-inch pipes through the heading. A puddle dam was constructed in the lined portion, and a large air-shoot, which had been used for ventilation, was lined with felt, and made available to carry off water. The construction of the permanent drain was then proceeded with. The quantity of water discharged by the shoot was ascertained to be 5,000 gallons per minute. When the culvert had been carried as far as the dam, the latter was removed, and the covered grip constructed up to the face of the headway. The heading was also raised in the lower place to prevent it from being again flooded, and driving was resumed on February 26, 1892. The difficulty of keeping the foundations of the side walls free from water was afterwards met by the employment of Tangye pumps, driven by compressed air. The quantity of water discharged from the fissure gradually diminished. From the fissure, onwards, the heading was driven at the formation level. At 2,090 yards dry shale was reached, and the heading was carried on a descending gradient to meet that from Totley, the junction taking place at 2,529 yards from the Padley entrance.

With regard to the hindrances unexpectedly caused by the quantity of water tapped at Padley, owing to the insufficiency of means to carry it off, it may be here remarked, that experience shows, that the best means of drainage during construction is a spacious grip in the centre of the heading, covered with timber, and therefore easily accessible; that the heading should not be carried below the formation unless the tunnel is inverted; and that the drainage of the foundation of the lengths of lining

is best obtained, in cases where there is much water, by the employment of compressed air pumps.

Timbering.—The timbering of Totley Tunnel is shown in figs. 9 and 10. In the section, five drawing bars are shown. The usual number was either four or five. In some places where the ground was good only three were used; at other places there were five or six, chiefly at the open ends. Fig. 11 represents the general section of the lining with the centering used during construction. The leading ribs were composed of three elm-planks bolted together, and the intermediate ribs of two planks. This figure also shows the sheet iron, which was put outside the brick-work to protect it from the water during construction, and which had been very successful in practice, for it must be remembered, that at both ends of the tunnel two large streams of water, amounting to two to three million gallons a day, were flowing, whilst from the crown, there would probably not drip enough to fill a $1\frac{1}{2}$-inch pipe. The Inspectors were each supplied with a printed book, in which they entered the thickness of the side walls, the number of miners excavating, and all other particulars. These returns were subsequently handed to the Resident Engineer, and were posted in the usual way.

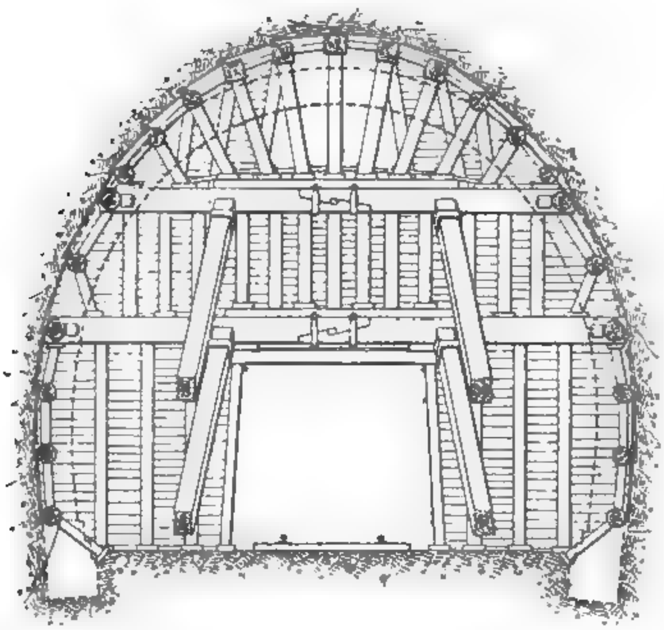
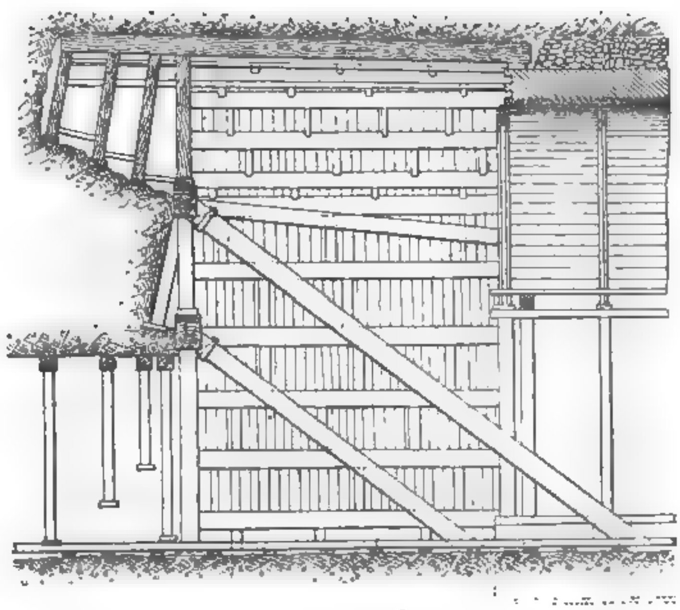


FIG. 9.

Compressed-air Machinery.—The whole of the headings, with the exception of 880 yards at Totley and 530 yards at Padley, were driven by

means of compressed air drills. In addition to these, compressed air drills were used in the top headings both at Totley and Padley. Compressed air was also almost the sole agent of ventilation. The plant laid down for the heading at Totley consisted, in the first instance, of one 10-inch Schram air-compressor, which was fixed at the No. 2 shaft, and two 3¼-inch Schram drills, the pipes being of wrought iron, 2 inches in diameter. When No. 4 shaft was reached in July 1889, this plant was superseded by an 18-inch Schram air-compressor, which was laid down there, and two 3½-inch Schram drills, the pipes being 3 inches in diameter. This plant remained in use until October 1890, when, at 1,740 yards, two 3¼-inch Larmuth drills were substituted for the two 3½-inch Schram drills, and with this plant the heading was completed. The plant laid down in each case served the heading only, except that one break-up was ventilated from the same pipe until March 1892, after which date, owing to want of pressure at the face, the pipes were used solely for the heading.



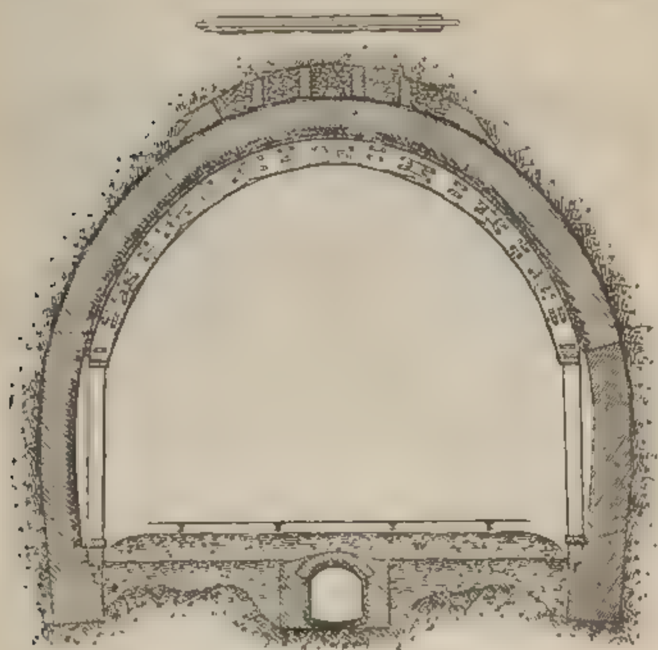
Scale. 1 inch = 10 feet.

FIG. 10.

The plant employed at Padley consisted of a 12-inch Schram air-compressor, driving two 3¼-inch Schram drills in the heading, through 2½-inch pipes, which also supplied air for ventilation. This plant was discarded in June 1890, when a 40-h.p. compound engine, driving two 16-inch air cylinders, was erected, and 4-inch pipes were substituted for

the $2\frac{1}{2}$-inch pipes to the face. In September, 1890, at 950 yards, the $3\frac{1}{4}$-inch Schram drills were replaced by two $3\frac{1}{4}$-inch Larmuth drills in the headings.

In November 1890, air drills were used in the lengths at Padley. The Fowler air-compressor being insufficient to work the whole of the drills and to supply air for ventilation, a second Fowler air-compressor, similar in all respects to the first, was erected, with $2\frac{1}{2}$-inch pipes to the heading; but only one air-cylinder was worked, the other being held in reserve. The $2\frac{1}{2}$-inch pipes were reserved entirely for the heading, no air being drawn from them either for the lengths, or for ventilation. The smaller diameter of the pipes, when the headings were within a few hundred yards of meeting at 2,529 yards, was found to cause a great deal of friction, the difference in air pressure between the compressor and the face of the heading, at a distance of $1\frac{1}{4}$ miles, when the machines were working, being sometimes as much as 15 lb. or 20 lb. per square inch. As break-ups were commenced in the rock and hard shale, additional drills were worked in the top headings of the lengths, the total number driven by the double compressor, besides the air supplied for ventilation, being two $3\frac{1}{4}$-inch Schram drills and two 3-inch Larmuth drills. For drilling the top headings, and for ventilation at Totley, the 10-inch Schram compressor



Scale 1 inch = 10 feet.

FIG. 11.

from No. 2 shaft and the 12-inch Schram compressor, which had been superseded at Padley, were laid down at No. 4 shaft, and were coupled to 3-inch pipes. In April 1891, these two air compressors were replaced by two 18-inch Schram compressors, coupled to a 4-inch pipe down the shaft, and 3-inch pipes beyond. These, in addition to ventilating, worked four

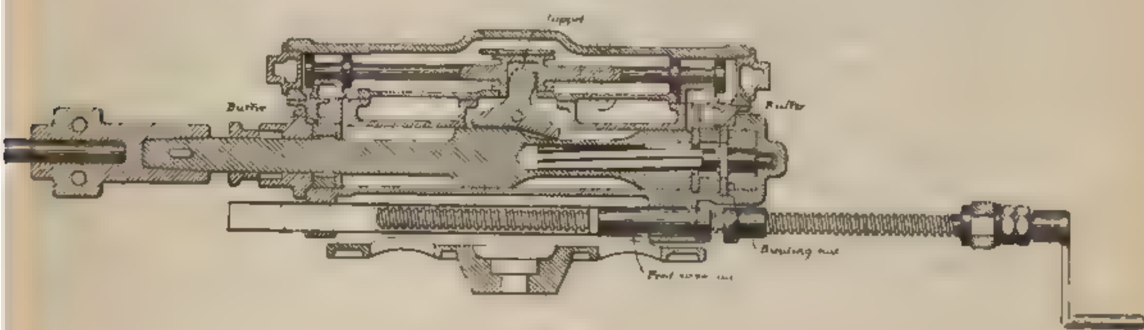


Fig. 12.

3-inch Larmuth drills, and one $3\frac{1}{2}$-inch and one $3\frac{1}{4}$-inch Schram drill in the top headings. In January 1892, one of the 18-inch compressors was converted into a low-pressure machine by the substitution of a 4-foot cylinder, and was coupled to an independent range of wrought-iron riveted

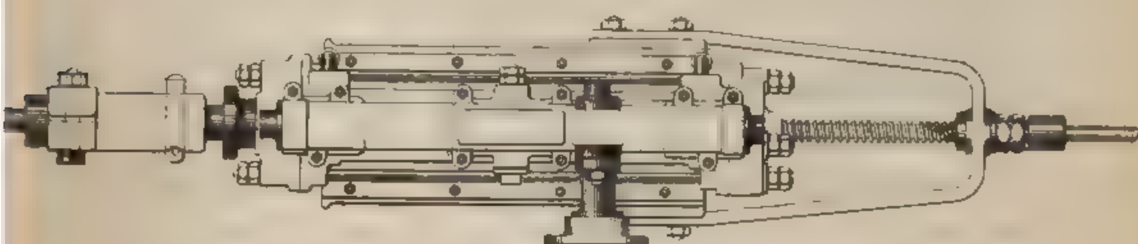


Fig. 13.

pipes, 8 inches in diameter, which were carried as far as 2,970 yards and used for ventilating purposes only.

The Larmuth machine drills were found to work most satisfactorily. Their special feature is the mode of actuating and locking the valve, which is effected by the piston through the medium of a tappet. The machines supplied to Totley Tunnel are illustrated by figs. 12 and 13. The piston is

long, and is turned to fit the cylinder truly, without packing. It has a recess in the middle of its length into which one end of the three-armed tappet drops, as the other end is lifted and held by the cylindrical part of the piston. The tappet is thus made to rock upon its pivot, and to actuate the valve spindle into which its upper arm is fitted. The valve spindle in its turn actuates the D valves, which fit between two collars on the spindle at each end. There is no air-cushioning at the front end of the cylinder, and a very hard blow is therefore obtained from the machine. In cases of overshooting, the momentum of the piston and drill is destroyed by a thick india-rubber buffer. The twisting motion of the drill is obtained by means of the usual square twist-bar, working through a nut in the end of a piston, which is moved round at each stroke, and is secured by ratchet and pawl at the back end of the cylinder. The long screw, by which the feed is supplied, has an arrangement for taking up the wear. A second binding nut is added, and each of the nuts has flanges cast upon it, through which two bolts pass. These are tightened up as the thread wears, and are secured by lock nuts. The machine is fixed in the usual way by a conical spigot cast on the under side of the cradle, which fits into a socket on the carrier, and is secured to it by a central bolt, whilst the carrier clamps the stretcher bar by two bolts. The machine can thus be moved on either a vertical or a horizontal axis, and be fixed in any position. The drills were found to work with very little attention in the way of repairs, as no packing of the piston was required, and it was not necessary to send them to the fitting shop, except for renewals. The chief wear occurred in the feed screws and nuts. The piston required renewal once every year. The only defects found in the machine, were the breakage of the valve spindle by the sudden shock with which it was actuated; and an insufficiency of strength in the cradle to resist the strain produced by the workmen hammering the drills when they had become jammed in the holes; but an improved form of the drill has, it is understood, now been brought out which is free from these defects. The selection of the machines was chiefly governed by their weight.

Method of Drilling the Headings.—The drilling apparatus in the bottom

headings consisted of two machines, mounted upon the horizontal stretcher bar, which was screwed tight across the heading. This was fixed seven feet from the bottom, and about four feet from the face of the heading. The two machines were worked from a benching, three feet six inches above the bottom, by four men; one man was employed to put on the feed at each machine, and the other two to water the holes and change the drills. The remainder of the gang were occupied in filling the débris from the previous round, fixing the timber, and laying the road. The size of the drill commenced with $2\frac{1}{4}$ inches diameter, diminishing by three or four successive sizes to $1\frac{1}{4}$ inch diameter, the full depth of hole in the shale being 6 feet 6 inches. The depth of hole in the rock was less and varied considerably according to the joints &c. The directions of the holes are shown in figs. 14 and 15, from which it will be seen, that the position of the machine on the bar remained the same for all the holes, the direction of each hole varying with its position on the face. The number of holes varied from round to round; in shale, ten to fifteen holes were sufficient, whilst in rock the number was greater.

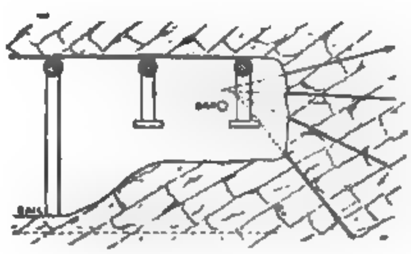
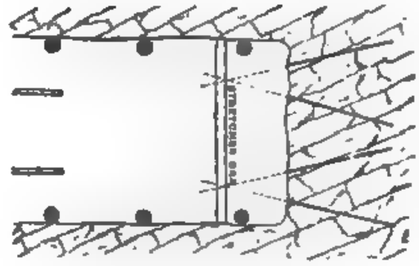


Fig. 14.



Scale 1 inch = 6 feet.

Fig. 15.

Explosives.—Gelignite was the only explosive used, and as the progress of the headings was of so much importance, no limit was set to the quantity that might be used by the miners. The consequence was that an excessive quantity was consumed, the holes being generally one-half or two-thirds filled. The holes were all charged together, but were fired in two or three series, primers, with detonators and fuse, being inserted separately for each series. The bottom series of holes was fired first, the inner holes of each series being given a start of the others. Sockets, when

they occurred, were only found in the shale in the upper series of holes. To clear the heading of dust and smoke after firing, the air pipe was turned off some distance from the face, and the pipe on the heading side was filled with water; the air was then turned on again, and the water discharged into the heading in spray. A few repetitions of this process were sufficient to render the heading clear enough for the men to return to work.

Progress of the Headings.—Previous to February 1890, the heading at Padley had been driven by hand power only; and, at Totley, the completion of the headings between the shafts was so urgently needed to liberate the water and permit lining to proceed, that they were not always driven to the full size, and no record of them was kept. From the commencement, at Padley a 4-foot 8½-inch gauge road, with 3-yard end-tip wagons, was employed to remove the débris from the face. At Totley, the size of the wagons was limited by the winding cages in the pit, and a double road, of 2-foot gauge, was laid down. Side-tip wagons were used, each holding ¾ cubic yard, and the trains of wagons were drawn by ponies. This arrangement was, however, found to be inadequate, as the number of break-ups to the west of No. 4 shaft increased. The double cages in the shaft were therefore replaced by a single cage in May, 1891, and a single road of 4-foot 8½-inch gauge was substituted for the double road. Side-tip wagons, each of 4 yards capacity, were then employed, until the completion of the work. Owing to the much greater quantity of lining being done at Totley than at Padley, a break-up was always in progress close to the face of the heading, and no room could be spared for a turn-out for the wide gauge. The train of wagons for the shaft had, therefore, to be run into the headings, and filled, one from the other, until the set was full. This required a large increase in the number of men in the heading, and not infrequently caused slight delays. At Padley, the heading was always much in advance of the break-ups, and a turn-out was kept for the heading wagons near the face, which obviated so much labour in filling. The number of men employed at the face of each heading averaged eight or ten at the commencement, and increased to nearly twenty per shift, the increase in the number being chiefly due to the larger number required for filling at

Totley, and for the construction of the temporary drain at Padley. The day was divided into 3 shifts, of 8 hours each, and, until the beginning of 1891, one shift only was worked on Sundays. After that date, it was optional for the men to work the other two shifts.

In Tables I. and II. the rates of progress are reduced to a seven days' week, after deducting all time lost by the men; but minor delays, not amounting to a full shift, due to accidents, meal hours, changing shifts, &c., are not deducted.

TABLE I.—TOTLEY AND PADLEY TUNNEL.
ADVANCE OF THE HEADINGS BETWEEN FEBRUARY 1, 1890, AND OCTOBER 23, 1892.

—	Totley Heading.	Padley Heading.
Machines employed:	Two 3¼-inch Larmuth drills	Two 3¼-inch Larmuth drills
Cross-sectional area of heading . sq. yds.	12·2	12·2
Total period . . . . . weeks	141	141
„ time lost . . . . . weeks	29	45
„ „ worked . . . . weeks	112	96
„ progress made . . lineal yards	2,300	1,897
Average weekly progress . . . „	20·53	19·76
Maximum „ „ . . . „	28	33
Average number of cubic yards excavated per week	250	241
Maximum number of cubic yards excavated per week	342	403

TABLE II.—TOTLEY AND PADLEY TUNNEL. AVERAGE WEEKLY ADVANCE.

—	Material.	Water.	Period of test.	Advance.
		By machine after February 1890		
			Weeks.	Yards.
Totley	Rock	Much	15	14·33
Padley	„	Little	10½	19·13
„	Rock and shale	Much	15½	16·8
„	Shale	„	32	18·56
„	„	None	14½	29·87
Totley	„	„	17½	22·61
		By hand before February 1890		
Padley	Shale	Much	34	16·6

With a view to obtain detailed information of the heading driving, the time occupied by each operation was taken during 137 successive rounds, the results of which are given in Table III. The time of excavating is reckoned from the time the heading cleared after firing, until the machines were re-started, although the filling of the débris was not completed until some time afterwards.

TABLE III.—HEADING DRIVING AT TOTLEY DURING 137 SUCCESSIVE ROUNDS, DECEMBER 10, 1891, TO MARCH 10, 1892.

Material, dry shale.

			Hours.	Min.
Drilling	Drilling	2 hours 47 minutes	3	48
	Changing holes	16 „		
	„ drills	45 „		
Firing	Charging holes	1 hour 38 „	2	23
	Firing	45 „		
Excavating			7	41
Lost			1	9
	Average time for the whole round		15	1

Machines employed	Two $3\frac{1}{4}$-inch Larmuth drills
Average number of holes per round	13·4
„ length of hole	6·25 feet
„ number of drills per hole	3·8 „
„ pressure of air at drill	49 lb. per square inch
„ temperature of heading when drilling	66° Fahr.
„ quantity of explosive per round	38 lb.
„ number of sockets per round	1·8
„ length of „ „	1 foot
„ width of heading	11 feet
„ height „	9·92 feet
„ area „	12·12 square yards
„ advance per round	5·74 feet
„ quantity excavated per round	23·18 cubic yards
„ advance per week	21·35 linear „
„ quantity excavated per week	258·76 cubic „

Ventilation.—Until the headings met, the ventilation beyond No. 4 shaft from Totley depended entirely upon air supplied by the compressors. In addition to the exhaust from the machines, 2-inch ventilating pipes

discharged air from the main in each break-up. Each of the 18-inch Schram compressors discharged 450 cubic feet per minute, whilst the 4-foot compressor, which replaced one of the 18-inch compressors in January 1892, discharged 2,000 cubic feet per minute. The smallest allowance per man was between April 1891 and January 1892, during which time, allowing 15 feet per hour for each candle, and reckoning one horse as equivalent to 5 men, the allowance per man was under 300 cubic feet per hour. At Padley, the ventilation was generally good; this was due to the large quantity of water streaming from the roof, which dissolved the exhaled carbonic acid and other soluble gases.

The progress of the heading at Padley was, however, frequently stopped by the discharge of impure air into the workings during certain periods, concurrently with every fall of the barometer.

The first occasion on which foul air was met corresponded with the first occurrence of rock; and in piercing 350 yards of this, the heading was stopped from this cause on seven different occasions, the delays aggregating seven days. For the next 1,450 yards, which was wholly in shale, no stoppage occurred from foul air, but, after passing the larger fissure in the rock at 1,880 yards, the heading was stopped on sixteen different occasions, an aggregate of twenty-one days being lost from that cause. In every case, the foul air was discharged from the fissure, when the air at the face was good, and the heading was stopped, owing to the lights being extinguished there. The impure air discharged there was insoluble, and the explanation seemed to be, that it was air, which had been robbed of its oxygen by the iron pyrites. To assist in the permanent ventilation the cross-section was enlarged, thus giving a width of 27 feet.

It may here be mentioned that there would appear to be nothing better for lining purposes than brindle bricks. Blue bricks are not considered suitable. In one case, where a very smooth glazed brick had been used, an invert had been blown up by hydrostatic pressure; whereas the brindle, a less expensive brick, was rougher on its surface, and, therefore, held the cement more tightly. In the case of the glazed bricks referred to, the bricks came away, leaving the face of the cement perfectly

smooth; but when the brindle brick was substituted, the strength of the invert was much increased, whilst, at the same time, the cost of the brickwork was much reduced.

Permanent Works.—Cross-sections of the Totley and Padley Tunnels are shown in figs. 16, 17, and 18, Plate XXII. For 1,940 yards from the Padley entrance, the side walls are of block-in-course masonry; the side walls for the remaining 4,289 yards were of brickwork in mortar, faced with brindled bricks. The arch is of brickwork throughout, faced with brindle bricks, set in Lias lime-mortar through the dry ground, and in Portland cement where there is water. The depth of the foundations below the rails is, in rock, 2 feet 9 inches, in hard shale 4 feet 3 inches, and in softer shale 5 feet 3 inches. The thickness of the masonry side walls, through rock, which was much jointed, is 1 foot 9 inches, through shale 2 feet, and in heavy ground 2 feet 3 inches. The brickwork side walls are of the same thickness as the arch, which is 1 foot 6 inches through rock, 1 foot $10\frac{1}{2}$ inches through shale, and 2 feet 3 inches in heavy ground. There are 434 yards of inverted tunnel near the Totley entrance, and 356 yards at the Padley entrance, the invert being of brickwork 1 foot 6 inches in thickness. Old English bond is employed throughout. The rings of brickwork, in the side walls and arches, are bonded together in pairs, the odd ring in 1 foot $10\frac{1}{2}$ in. work being in the centre. Small manholes, 7 feet by 3 feet 6 inches by 1 foot 6 inches, are built at every chain, at alternate sides of the tunnel; and large manholes, 10 feet each way, are constructed at every half-mile for the convenience of plate-layers.

A 2-foot 9-inch culvert of brickwork in cement is built under the 6-foot way, and extends 2,112 yards from the Totley entrance and 1,920 yards from the Padley entrance. An 18-inch glazed and socketed drain-pipe, bedded half-way in cement concrete, laid with open joints, and covered with rubble, is laid for the remaining distance. Manholes, 4 feet by 2 feet 9 inches, are built in the culvert, and drain opposite every fourth manhole in the lining throughout the tunnel. Weep holes are left in the culvert at every 6 feet on either side. 4-inch pipe drains, covered with broken stone, are laid across the formation, at intervals of 2 chains, to drain the

foundations of the side walls. Weep holes were left in the side walls, two on each side in every length; and, in all wet lengths, 3-inch drain pipes lead the water from the arch to the weep holes. At each end of every wet length, a collar of brickwork, 9 inches wide by 4½ inches deep, projects from the arch, to prevent the water from running down the gradient of the tunnel, and finding its way through the mortar joints of dry lengths.

Shafts Nos. 1, 2, and 3, are 10 feet in internal diameter. They are lined in brickwork with mortar, not less than 9 inches in thickness, and faced with brindled bricks. No. 4 shaft (figs. 19 and 20, Plate XXII.), is 15 feet in internal diameter, and is lined with brickwork, in cement, on account of the water. The brickwork is not less than 18 inches in thickness, built solid to the ground, and is likewise faced with brindled bricks. To prevent the possibility of the shaft at No. 4 being crippled by the excessive weight of the shaft lining, the lining is broken off at 75 feet from the crown of the arch (fig. 19), and the upper part is set off to an 18-foot internal diameter, upon a bed of rock which lies at that level, and is coned over, at an inclination of 1 in 32, until the 15-foot diameter is reached. Two additional sets of footings project from the outside of the lining, at uniform heights between the foundations of the coning and the surface.

The tunnel fronts (figs. 21 and 22, Plate XXII.) are built of block-in-course masonry, with millstone grit arch-quoins, and tooled ashlar cornice and parapet.

A most important point in dealing with long tunnels is at once to put in thoroughly efficient drains. A very full-sized drain is, in fact, an economical thing; and further, it should be a drain, not inaccessible in a pipe, but covered with flags, so that it may easily be opened if there should be a stoppage.

In the Totley Tunnel, the brindled-brick lining was laid in alternate courses of 4½ inches and 9 inches, so as to bond the work properly together. The work was not built in single 4½-inch rings, but the 1-foot 10½-inch work was built in two 9-inch rings, with 4½ inches in the centre, bonded where they came together.

The Lining.—For the construction of the lining, the contractor was

fortunate in having close at hand the Totley Moor brick works, where very good common bricks were obtained. The brickyard was about half a mile from No. 4 shaft, and at a slightly higher elevation. A light tramway was laid down, and the bricks, after being examined, passed, and counted, were sent down the shaft in tunnel wagons. The brindled bricks were forwarded from Staffordshire to Dore and Totley station. Until the headings met, all the bricks for the lining at Padley had to be carted or sent by traction engine from Totley; and, as men were scarce at Padley, owing to its isolation and the excessive quantity of water in the workings, the quantity of brickwork done there was much less than at Totley.

The total number of break-ups was 51; their position was determined by the ground, very wet places being avoided, in the expectation that by leaving them for a time the quantity of water would gradually diminish. This expectation was generally realised, but, on the other hand, in many cases ground, which was quite dry before a break-up was commenced, proved the reverse when broken into. Where the ground for a long distance was continuously dry, the break-ups were made at uniform distances of about 100 yards. The number of lengths was 1,128, the most common being 15 feet and 18 feet long, the former being worked in the softer more perishable shale, and the latter in the hard shale. In the soft shale the lengths were 10 feet, and in the running sand and detritus at the west entrance, 9 feet lengths were worked. The brickwork for break-up lengths, and in some cases the side lengths also, were in every case built a ring thicker.

During the construction of wet lengths, special precautions were taken to keep the water from the work until the joints had set. Felt was used at first, being fixed outside the timbering; but sheet iron was afterwards used with more success. This was rolled to the thickness of 28 B.W.G., and was fixed in the same way as the felt. Owing to its extreme thinness, it yielded readily to pressure, whilst the space behind the brickwork was being packed, and yet stood the firing of the shots without being injured.

Before commencing to break up in very wet places, it was found

advantageous to drive the top heading through from the previous break-up. By this means the water was carried away through the heading, and the men were thereby spared the discomfort and inconvenience of breaking up amid streams of water from overhead. With the exception of those used in the top headings, no machine drills were employed in excavating for the lining. In the lengths, as in the bottom headings, gelignite was the only explosive employed, the total quantity consumed in the tunnel being 163 tons, or 52·3 lb. per lineal yard. As junctions were made between the break-ups, and the continuous lining from the entrance increased in length, locomotives were taken further into the tunnel and used for haulage, horses being used in the headings and break-ups beyond. Turn-outs in the break-ups, except in cases where they were unusually far apart, were not found practicable.

Winding Engines.—The winding engines employed at the No. 4 shaft were of the double-cylinder horizontal type, having cylinders 22 inches in diameter and with a 4-foot stroke, working at 70 lb. pressure per square inch. As gas was not available at No. 4 shaft, an electric lighting plant was laid down there, to illuminate the workshops and engine sheds. The pit-bank was also illuminated at night by 500 candle-power glow lamps. At the bottom of the shaft were two 50 candle-power lamps, and for 300 yards, the shunting operations were illuminated by 16 candle-power lamps, spaced 50 feet apart on alternate sides of the tunnel.

As the opening of the whole line from Dore to Chinley depended upon the time occupied in the construction of the Totley Tunnel, it was of the utmost importance that it should be completed within the shortest possible space of time. In this connection, it may be mentioned that during the year preceding the junction of the headings, the material being dry shale, 1,000 lineal yards of heading were driven, and over 1,500 yards of lining were built at that end alone.

The last length of lining was keyed on August 4, 1893, and the tunnel was completed and the permanent way laid by September 2, 1893.

One remarkable circumstance was the accuracy with which this tunnel, 6,300 yards in length, was set out, and the fact, that when the two headings

met, they were not above $4\frac{1}{2}$ inches out of the centre line. The time during which the tunnel was under construction was about five years, which showed a rate of advance of about $3\frac{1}{2}$ lineal yards per day.

The experience gained in the construction of this tunnel appears to suggest that more use should be made of concrete in the lining of tunnels, especially when the water has been removed, or where the outflow of water is but moderate. Concrete was exclusively used in two tunnels on the North British lines from Forth Bridge to Perth. One of these was lined entirely with concrete, and, in the case of a tunnel through rock, concrete has been shown to be far better than either brickwork or masonry, if good material be available, for the reason that, if properly put together, every inequality is filled up by the former. One of the tunnels on the Glen Farg line has also been built of concrete, including the arch, and the results have been most satisfactory. The concrete in this case was made of broken whinstone and some sand, in the proportion of six parts of stone and sand to one part of concrete. Some holes were made in it for the Government Inspector, who pronounced the work to be infinitely better than brickwork; and all who have had experience of tunnels are aware of the trouble that generally arises with tunnel bricklayers and their labourers. In the concrete tunnel, a good foreman was able, with ordinary labour, to put in the lining.

Reference may here be made to a new and peculiar form of locomotive which was used in the construction of the Duckmanton and Bolsover tunnels. This locomotive was so designed, that it could work through a 9-foot heading. Tip wagons of the ordinary size were used. The trucks could, therefore, be hauled out in a much shorter time and with much greater convenience, than by any arrangement with horses or hand labour. The locomotive drew the wagons right away from the heading to the tip. It was practically the same as the ordinary contractor's locomotive, except in the peculiar design of the footplate, which was so low that the driver's head was only about 8 feet above the level of the rails, and the funnel, by a telescopic arrangement, shut up when the locomotive entered the heading. The plan adopted for working these tunnels was to excavate

the cutting at the face to within about 20 feet of the formation, and then to form an inclined line, with a gradient of 1 in 16, down to the mouth of the tunnel. This greatly expedited the construction, the headings being driven at the rate of about 10 yards per week from each face.

In connection with the use of compressed air for driving the pumps, it may be stated that, when previously used, it had been found to be an expensive method, both at the Blackwall and Hudson Tunnels. At the former, there had been a considerable amount of water, which, working down grade, had all run to the face. The air did not seem to be cooled as much as it should have been by the water jacket, and, owing to the heating of the air during compression, about 25 per cent. of the work done was lost. To the contractor this is a serious matter. To obviate this, it was arranged to put water jets into the cylinders, so that the air might be cooled whilst it was being compressed.

An invention has been in existence for many years, which has for its object the transmission of power to long distances, not by compressed air, but by exhaustion, the engines being worked, at the ends of the main, at about half an atmosphere of pressure. In the exhaust pump, precisely the same thing occurs with regard to generation of heat, as in the compressor pump; that is to say, the air, in passing through the mains, becomes heated practically to the temperature of the earth; it then comes into the pump, is exhausted, then the piston returns and compresses the air to atmospheric pressure to open the head valve and escape, and in this way heat is generated, just in the same way as in the compressor pump.

Cost.—The actual cost of the tunnel cannot at present be definitely stated, but approximately the Totley Tunnel has cost something like 75*l.* or 76*l.* per yard; the Cowburn tunnel, of which a description follows, 2*l.* or 3*l.* per yard less; and the Dore Tunnel—excluding the fronts, which in a short tunnel amounted to a considerable portion of the total cost—about 53*l.* or 54*l.* per yard.

With regard to the time occupied, the average progress was about 3 or 4 yards per day. In the earlier stages of the work, owing to considerable difficulties with the water and the men, the progress was not so rapid, but

latterly the rate increased considerably. From July 1889 to July 1890, the rate of progress was only 16½ yards per week; but from July 1892 to July 1893, it rose to 48 yards per week.

The geological formation from the Totley end to near No. 4 shaft was the lower coal measures, and at the Padley end it was millstone grit and shale. Very few bars were built in, except at the junction lengths, and as there was no great weight upon the timber in any part, nearly the whole of the bars were subsequently removed. The levelling was done in the usual way with an ordinary spirit level.

COWBURN TUNNEL.

Situated at the head of the Edale valley, out of which it springs almost perpendicularly, the arm of the Peak known as the 'Cowburn' rises to an elevation of 1,700 feet above the sea. The tunnel (fig. 23, Plate XXI.) cuts the axis of the hill at right angles, and lies in a west-south-westerly direction at its base. It is 3,702 yards long, and is straight from end to end. The gradient rises from the Edale entrance, at an inclination of 1 in 1,000 for the first 913 yards, to the summit of the Dore and Chinley Railway, and then falls to the Chinley entrance, at the rate of 1 in 150, the difference in level between the two ends being 53 feet.

Alignment.—The centre line was first approximately laid out with a 6-inch theodolite. A portable transit instrument, with 20-inch telescope by Stanley, mounted on three legs, similar to the smaller instrument, was then employed. Two points, three-quarters of a mile beyond the Chinley entrance in the approximate line, were then taken as fixed, and from these the line over the tunnel was set by the larger instrument on pegs, driven into the ground at every change of surface, and on two pegs in the Edale valley, situated 70 chains apart beyond the eastern entrance. This operation was repeated many times, until the centre line was exactly established. Hollow observatories of masonry, 6 feet by 4 feet, capped [illegible] from 6 to 8 feet in height, were built over t

beyond each end of the tunnel were surrounded with masonry to prevent their being disturbed. The centre line was then transferred from the pegs to the stone caps. From the centre line thus obtained, the shafts were set out, and the line was produced into the headings from both ends by means of the 6-inch instrument only. When the headings met on July 18, 1891, at 2,305 yards from the east entrance, the difference in line between the two headings was found to be less than one inch.

Shafts.—Owing to the ground rising steeply over the tunnel at each end, there is only one permanent shaft, situated at 335 yards from the Edale entrance, and 10 feet in internal diameter. A temporary shaft was also sunk at the east entrance. In sinking the temporary shaft, successive beds of shale and rock were passed through, which brought in large quantities of water, the quantities discharged by the pumps reaching over 20,000 gallons per hour. The permanent shaft was commenced on October 3, 1888, and was sunk through shale and several bands of rock, the quantity of water yielded amounting to 24,000 gallons per hour.

Headings.—The size of the tunnel heading was 10 feet by 9 feet clear of timber, and was driven at formation level. For 120 yards beyond the permanent shaft, there was a considerable quantity of water, but for the remaining distance to the junction the heading was dry. The material for the first 1,170 yards was shale, the remaining length consisting of rock intermixed with thin beds of shale, which was found very difficult to pierce. A commencement was made with the heading at Chinley on November 26, 1888, the material pierced being rock, accompanied by a little water for the first 1,300 yards, the remaining distance to the junction being dry. The strata throughout the tunnel dip, towards the west, at about 1 in 16 At Chinley, only 234 yards were driven by hand, after which compressed-air machinery was brought into use. The plant consisted of one 12-inch Larmuth compressor, and one 12-inch Fawcett-Preston compressor, working two 3½-inch Larmuth drills mounted on a drill carriage, the pipes being of cast iron, 6 inches in diameter for the first portion, and afterwards of wrought iron 3 inches in diameter. The drill carriage was soon discarded for the simple stretcher bar, as the necessity for removing

the débris and laying the road at every round, before the machine could be brought into action again, proved a serious hindrance to progress.

For 1,070 yards from the Edale entrance, the heading was driven by Elliott hand-power ratchet drills. The progress obtained by the employment of these drills in soft material proved greater than by the use

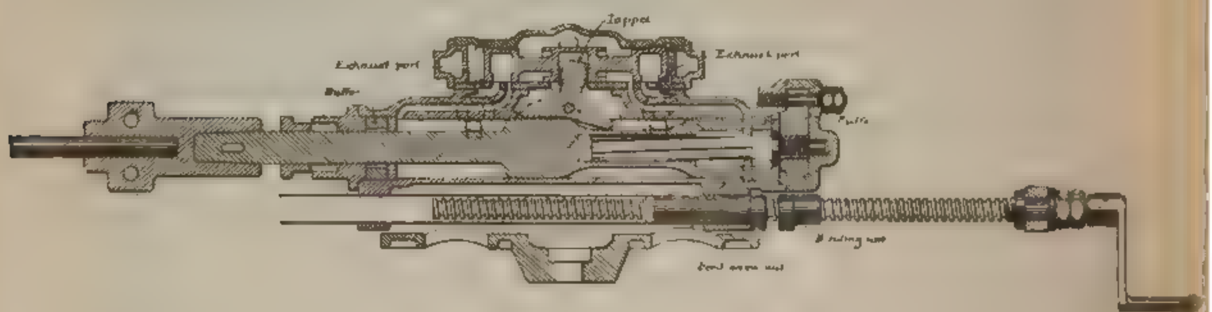


FIG. 24.

of compressed-air machinery. The drills are handy, take up but little room, and three or four can be at work simultaneously. The compressed-air machinery, afterwards used as the ground became harder, consisted of a 16-inch compressor, working two $3\frac{1}{4}$-inch Larmuth drills, the air-pipes being of cast iron, 6 inches in diameter for the first portion, and wrought iron, 3 inches in diameter, beyond. The progress of the Edale heading

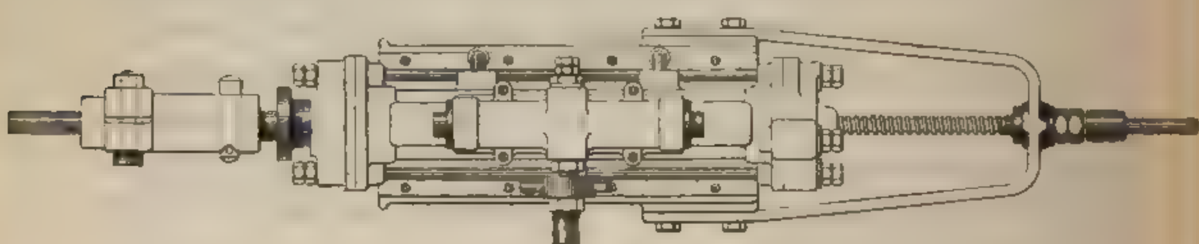


FIG. 25.

was stopped for six or seven weeks, owing to the appearance of dry rot in the timbering, and over 1,000 yards of heading had to be re-timbered. Old iron rails, bolted together, side by side, with a flitch of timber between them, were then largely substituted for timber head trees. The pressure upon these, however, was so great that many failed and had to be renewed.

After the bottom headings met, the drills were transferred to the top headings of the lengths, and additional 3-inch Larmuth drills were also employed. An air-receiver was at the same time placed in the tunnel on the line of pipes, to increase the pressure at the drills, with satisfactory results—the difference in pressure between the compressors and the drills being reduced to only 5 or 6 lb. The improved Larmuth drills (figs. 24 and 25) latterly supplied to the Cowburn Tunnel had not the defects of those previously referred to (p. 379). The chief alteration consists in the substitution of a solid piston valve for the valve spindle and D valves, which are actuated by air from the valve chest. The tappet, however, is retained to insure certainty of action, and to lock the valve in position. This arrangement has the advantage of reducing the wear of the tappet and main piston, besides removing the cause of the fracture of the valve spindle, common in the old pattern. The cradle of the new pattern has been strengthened, without adding to the weight, by the substitution of aluminium crucible cast steel for cast iron. Also the square twist-bar, which wore rapidly at the corners and frequently broke, has been replaced by a grooved bar, which removes both those defects; the new machines are made with either a long or a short valve chest, the latter being lighter whilst the former is more economical of air.

The explosive, used in the headings and in the lengths, was gelignite, the total quantity consumed being 96 tons, or 51·8 lb. per lineal yard of tunnel.

A record of the progress of the heading was kept, from which Table IV. has been prepared. No work was done on Sundays, but the progress has been reduced to a seven-days week.

TABLE IV.—COWBURN TUNNEL: AVERAGE WEEKLY ADVANCE OF HEADINGS.

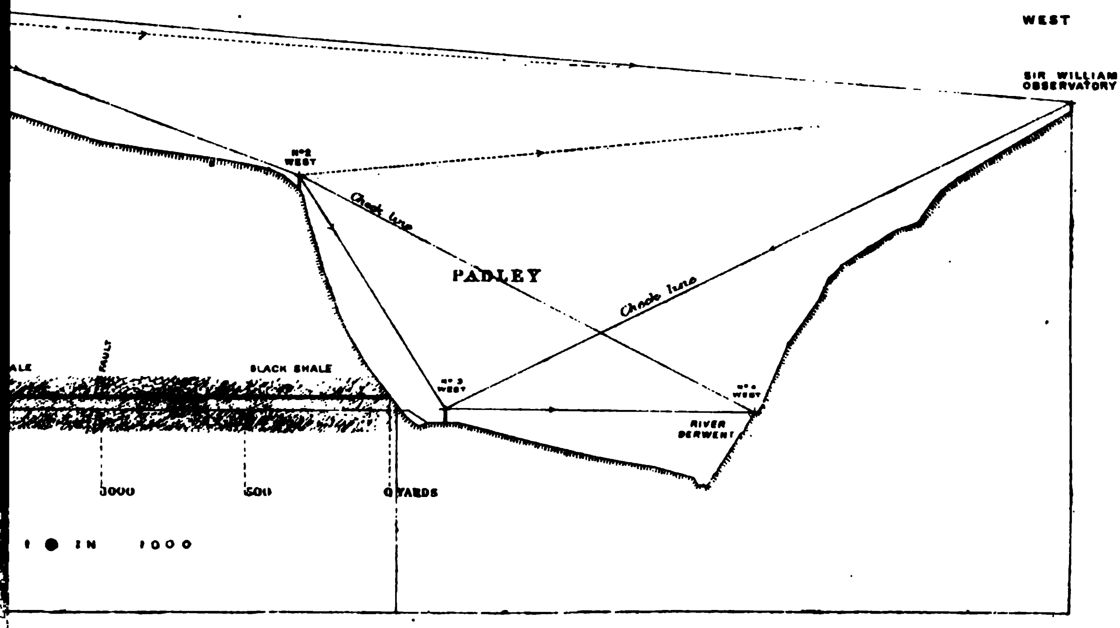
—	Material.	Period of test.	Advance.
		Weeks.	Yards.
Edale, by Elliott hand drills	Dry shale	34	23·25
„ machine drills	Shale and rock	69	21·0
Chinley, by hand	Rock	24	8·6
„ machine drills	„	75	15·5

The cross section and construction of the lining of the Cowburn Tunnel are similar in all respects to those of the Totley Tunnel. For 2,180 yards from the Chinley entrance, the side walls are of masonry, the remainder being of brickwork. As the ground is free from water, no culvert is required, 9-inch pipes being laid on each side to take any weeping which may occur. The absence of water favoured the construction of the lining in a more systematic manner than at Totley. The break-ups were made at uniform distances of about 85 yards, and as the junctions successively occurred, locomotives were taken further in the tunnel to remove the spoil. The ventilation of the workings was also more effectively maintained by this arrangement. A fan, 16-foot diameter by 4-foot, was erected at Chinley, and this exhausted the foul air through a 5-foot by 3-foot shoot, which was laid as far as the continuous lining was constructed, and was carried forward as junctions were made in the lining.

Owing to the difficulty of access to the Edale valley, little was attempted with the lining there, until the headings met. This allowed greater opportunity for pushing forward the heading from that end; whilst at Chinley the progress of the heading suffered, to some extent, through the vigour with which the lining was pushed forward. The last length of lining was keyed on December 22, 1892.

DORE TUNNEL.

This tunnel, although only four chains in length, is worthy of notice on account of a certain peculiarity possessed by it. It passes under very steep side-long ground, at no great depth, and is on a curve of 12 chains radius. In order to allow for the necessary canting of the vehicles on so sharp a curve, and at the same time to enable the tunnel to sustain the unequal load imposed upon it, the cross section is inclined from the vertical towards the inside of the curve to fit the super-elevation of the outer rails of the permanent way (fig. 26, Plate XXII.).



Horizontal scale for figs.

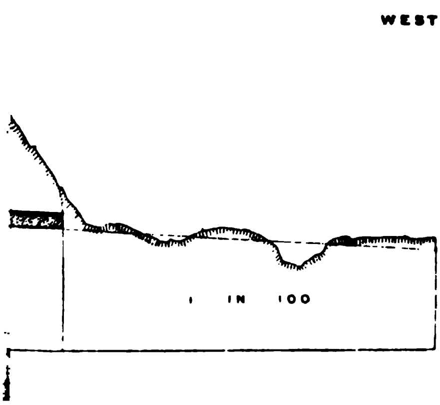


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Plate XXII.

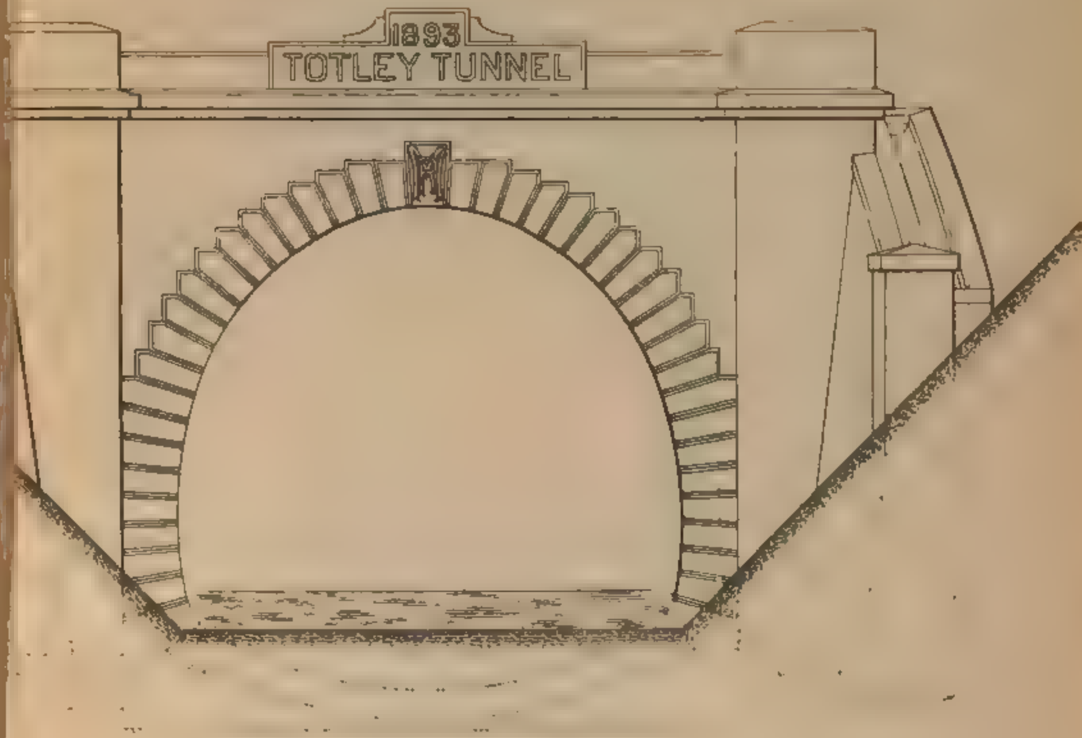

Fig. 21. Elevation of Tunnel Front.

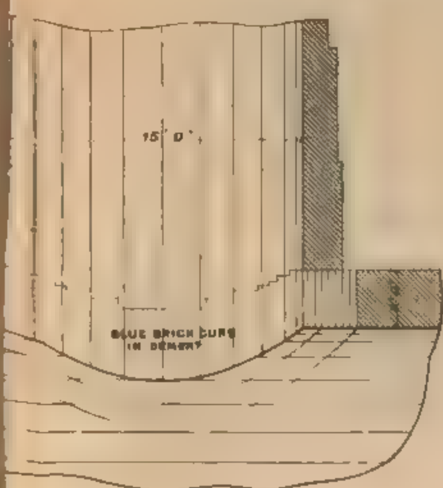

Fig. 20.

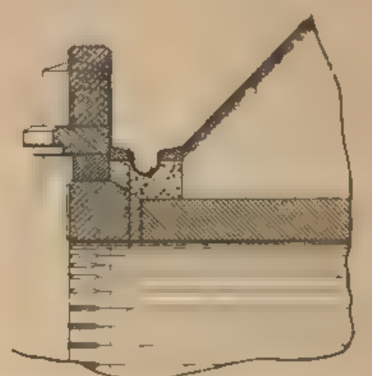

Fig. 22. Longitudinal Section through Keystone.

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CHAPTER XXIX.

TUNNELLING THROUGH HARD AND SOFT ROCK (SANDSTONE, MICA SCHIST, ETC.).

GLASGOW WATER WORKS: TUNNELLING FOR THE NEW AQUEDUCT.

THE new aqueduct, in course of construction from Loch Katrine, for the purpose of establishing a water supply for the city of Glasgow is 23½ miles long, of which 18 miles and 78 chains are in tunnel. In order to spread the expenditure over a number of years, it has been determined to delay the boring of the first tunnel, and for the present to use the existing outlet for the new aqueduct (fig. 1, Plate XXIII.). This tunnel is 2,352 yards long, and will be made through a hill which rises precipitously on either side to a height of 512 feet, the geological formation being the Lower Silurian, with whin dykes intersecting. The same hill was penetrated thirty-five years ago for the old aqueduct; and for that purpose ten shafts were then sunk, some of them to a depth of 500 feet. There were not then at hand the same appliances for tunnel boring as at the present day, and it may be anticipated that the later tunnel will be driven at a greater speed, and possibly without shafts at all. The work connected with the construction of the old aqueduct occupied some four years.

The profiles shown in figs. 1 to 8, Plate XXIII., illustrate the complete length of the new aqueduct, which commences at the point where the waters of Loch Arklet pass into the lake, about 2½ miles above the present inlet. But for the present, the whole of the water will pass through the old aqueduct for a distance of 2,352 yards, and thence, by means of a

junction aqueduct, to either the new or the old aqueduct, or to both.

There are in 'cut-and-cover' 1 mile 34 chains, and of piping 3 miles 8 chains. The construction of the aqueduct was divided into eight contracts; the making of the new service reservoir being the ninth, and the laying of the mains from the reservoir to the city the tenth.

Particulars respecting the various contracts are appended in tabular form.

Name of contract.	Length.		Tunnel.	Contract price.[3]	Name of contractor.
	Miles.	Chains.	Yards.	£	
Loch Katrine tunnel	1	26	2,420	—	Not let
Loch Chon	3	32	5,281	70,338	J. Waddell & Sons, Edinburgh
Duchray[1]	2	62	4,368	51,000	George Lawson, Rutherglen
Kelty	3	41	5,510	67,000	George Lawson, Rutherglen
Black Rigg	3	11	4,410	87,000	Morison & Mason, Glasgow
Endrick Syphon	2	34	—	—	Not let
Blane Valley[2]	5	34	9,585	114,500	James Young, Glasgow
Mugdock[3]	1	45	2,674	40,000	Morison & Mason
Craigmaddie Service Reservoir[4]	—	Acres. 86¼	—	177,000	Morison & Mason

[1] Includes two aqueduct bridges of masonry and concrete, 42 feet and 57½ feet span respectively.
[2] Includes ¾ mile double line of 48-inch pipes, concrete and masonry bridges.
[3] Some of the contracts exceed the original amounts owing to extras.
[4] Of the trench, 167,000 cubic yards were excavated up to February 1894.

The aqueduct is mostly through hilly country, the strata consisting geologically of metamorphosed mica schist of the Lower Silurian system, which is very hard and most insoluble. But towards the southern end of the aqueduct, red and white calciferous sandstone is met. In some cases the material has been found hard enough to dispense with lining, whilst in some parts lining was found to be necessary. The sections adopted for the work are shown in figs. 9 to 30, Plate XXIII., and it may be explained that the drain shown on some of these was only for temporary use. In all cases, too, a concrete invert was ultimately adopted, even where no lining was required. The tunnel is from 9 feet to 9 feet 6 inches high, and the maximum width is 12 feet where unlined, and ten feet where lining is required. This greater width where the tunnel is unlined was

dictated by experience, for in the old aqueduct it was found that the rough edges offered such a resistance to the flow of the water as to reduce the quantity passed by about 35 per cent. The inclination, as in the old aqueduct, is 10 inches to 1 mile, and the water will run 7 feet deep. The walls have a batter of 1 inch per foot, and there is a rise of arch of 3 feet, whilst the invert has a versed sine of 6 inches. (Figs. 29 to 30, it may be explained, are sections of the aqueduct where it passes under burns.)

The lining is of concrete, the proportions being three parts stone, broken to pass through a 1½-inch ring, two parts of sand, and one of cement. The concrete was all hand-mixed, the different proportions being accurately measured, and turned over twice dry and thrice wet. The cement had to stand a tensile strain of 350 lb. per square inch of section one week after the briquettes had been made. As to the concrete, experiments were made frequently with bars 4 inches square, placed between bearings 2 feet apart, and they had to stand on an average a transverse strain of 400 lb. The bars, of course, were made up from the material in use.

The stonebreakers broke on an average 35 cubic yards per day, the cost being as follows:—

	£	s.	d.	
Eight labourers at 3*s*. 6*d*.	= 1	8	0	
Engine man	0	3	4	
Coal	0	12	0	
Use of plant, say	0	3	0	
Total	£ 2	6	4	for 35 cubic yards

This is equivalent to a cost of 1*s*. 4*d*. per cubic yard. To this must be added, 1*s*. 4*d*. for lordship and quarrying, and 1*s*. 2*d*. per yard for transit expenses for two miles, bringing the total cost to 3*s*. 10*d*. per cubic yard of broken stone. Sand crushing cost about the same sum per diem as stonebreaking, but only about 27 cubic yards were produced, so that the cost per cubic yard amounted to 1*s*. 9*d*. Only waste stone was used, but, allowing for quarrying and lordship, say 1*s*., and an equal sum for transit,

the total cost per cubic yard of sand amounts to 3*s.* 11*d.* The actual cost for lining 300 yards from mixing platforms was as follows :—

	s.	*d.*	£	*s.*	*d.*
Labour, mining, &c. (1¼ cubic yards per man-day) at 4*s.* 6*d.* per day	3	7			
Labour, setting, centering, &c., 8·8 cubic yards (15 square yards) at 5*s.* a day	0	7			
Traction and ventilation	0	8			
Total for labour			0	4	10
Two-thirds cubic yards broken stone at 3*s.* 10*d*			0	2	7
Two-fifths cubic yards of crushed sand at 3*s.* 11*d.*			0	1	7
Cement at 50*s.* per ton, ¼ ton =			0	12	6
Sundries, say			0	1	6
Net cost of concrete per cubic yard			£1	8	0

In places were the roof was exceptionally bad, the cost of labour sometimes amounted to double the above—*i.e.* to about 9*s.* per cubic yard—so that in such cases the total worked out to 27*s.* per cubic yard.

The work in progress began with the Loch Chon contract (fig. 1, Plate XXIII.), which connects with the old aqueduct, at 1 mile 30 chains, by means of a concrete channel and stop-plank chambers, to which reference will be made hereafter, and passes in a south-easterly direction for 3 miles 32½ chains. The work consists chiefly of tunnelling through the Lower Silurian formation, with a few short lengths of open cutting. There are four long tunnels (fig. 1). These are the Blairuskin, three-quarters of a mile long; the Dow of Chon, nearly a mile long; the South Frenich about half a mile long; and the North Frenich, a little over three-quarters of a mile long. The hills are pretty steep, and the contractors adopted the plan of running in drifts at several points of the line of tunnel; but, in addition to the adits, several vertical shafts were sunk, of which five were temporary, while three will remain for ventilating the aqueduct and for access. These vary in depth from 33 feet to 60 feet, and the temporary shafts from 27 feet to 54 feet. The surface level at the highest point is about 400 feet above the bottom of the tunnel. This, however, is exceptional, being a crag in the Dow of Chon. Throughout the 5,000 yards of tunnelling there were

16 faces, and at several of these compressed air drills were at work, the progress made varying according to the nature of the material; but in the hardest of the whin 26 feet were driven in a week. The material generally is so hard that no lining will be required, except for a few yards at the entrances to the tunnels, where the rock shows a tendency to decay on exposure.

Blairuskin Tunnel (fig. 1), 1,319 yards long, was started in October 1892, and was completed in January 1894, so that it took, driving from both ends simultaneously, fifteen months, the average progress at each face, therefore, being about 44 yards per month. What is possibly of more interest, is the cost of driving through this hard Silurian clay and slate. A Larmuth rock drill was used, working with 60 lb. pressure. There were twenty-two holes in the round, of a depth of 3 feet 6 inches to 4 feet and of $1\frac{3}{4}$ inches diameter, and the average time to each length of hole was seven to nine hours. One of the holes was bored in thirty minutes. The number of men engaged was two miners, four labourers in the tunnel, and one engine man. The miners get 6*s*. 6*d*. per day, the labourers 4*s*. to 4*s*. 6*d*., and the engine man 3*s*. 6*d*. The average weight of stuff removed at each firing was about 26 tons—thirty to thirty-five wagons of 16 cwt. each. This was moved off to the spoil heap in wagons by a horse, the horse and driver costing about 8*s*. per day. It was found that one shift in their day's work cleared off the stuff fired by the preceding gang and themselves fired another, so that the day's work and cost, as represented above—27*s*. —represents the labour cost of removing one firing, or 26 tons, or about the cost of three lineal feet of the tunnel as shown in section, *plus*, of course, the cost of mechanical drilling and tool sharpening. On the Loch Chon section, it may be stated, gelignite was used, 25 lb. to 27 lb. being needed for each round. This large quantity was due to the hard nature of the rock.

The portion of new aqueduct forming this contract crosses below the old aqueduct at four different points. On none of the other sections now in course of construction has similar work been done. At the crossing near Loch Dhu, the work was particularly interesting, for there it crossed on

the site of an access chamber and on a very awkward skew. This caused a considerable amount of excavation, and, as the old aqueduct had to remain dry during the operations, they were carried on day and night. Over 400 cubic yards of hard tile, which had to be blasted, were removed, and in the course of construction of the channel of the new aqueduct over 200 cubic yards of concrete were put in, and yet the work was done, and the water flowing again through the old aqueduct in five days and a few hours from the start.

The section passes along the western shore of Loch Chon, and as the roads are hilly and not well adapted for the carriage of material, the contractors recognised the advantage of adopting water transport where possible. They, therefore, built a flat-bottomed boat and put a steam launch on the waters of the loch, with the result that the work progressed more rapidly.

The Duchray and Kelty contracts were entrusted to Mr. George Lawson, of Rutherglen, Mr. H. A. Caffin being engineer and Mr. George Smith resident engineer on behalf of the Glasgow Corporation. In the two contracts there are six tunnels extending to 9,878 yards, or over 5½ miles, and it is interesting to note, that although they were for the most part through rocks, it has been considered desirable to line 3,900 lineal yards, made up in part of side walls and arch and part of side walls only. In other words about 40 per cent. of the total extent of rock was unfit to be left unlined. The longest tunnel is that known as the Kelty—4,594 yards, or 2 miles 5 furlongs, long, and about 250 feet below surface level (fig. 3). It has been driven from either end, and from two shafts about 60 feet dip. The two most distant faces were 3,375 yards apart.

Tunnelling was started in June 1887, and was completed December 28, 1889. The average rate of progress between the shafts was 36 yards per month of four weeks, or 18 yards per week—9 yards at each face. Operations at each face were carried on by two 10-hour shifts of 8 men each, but afterwards three 8-hour shifts were adopted with 6 men to each. The contractors found the 8-hour shifts to be more economical; but, as proving that it is not always safe to generalise on one experience,

it will presently be shown from carefully prepared data, that the ten-hours, in other cases, was proved to be more economical than the eight-hours shift.

The two faces of the Kelty Tunnel met exactly as to line, and there was only two inches' difference of level. This being the longest tunnel on the works, some general details may not be uninteresting. Operations at the south end were commenced June 1887; and, meanwhile, two shafts were sunk, the one 264 yards from the north end and 69 feet deep, while the south shaft, No. 2, was 755 yards from the end and 72 feet deep. The work was carried forward at the south heading by hand for a distance of 12 chains, before the use of compressed air was introduced. Operations at the bottom of shaft No. 2 were started in August 1887. Southwards towards the end of the tunnel the driving was by hand, and a junction was made with the south end in March 1889. After this the shaft was abandoned, and all spoil removed through the open end. Two compressed-air Hirnant rock drills, to be described later, were put in at the shaft, and these were utilised at the head working northwards. Great difficulty was experienced in boring through a bed of conglomerate 10 to 12 chains thick, through which the rate of driving was about 24 lineal yards per month. After this the material improved, and an average rate of 44 lineal yards per month was maintained.

In the north end, operations were commenced at the bottom of the shaft No. 1 in December 1887. Two months' driving was done from the open cutting at the north end, and a junction was effected between the shaft and the open end in October 1888, after which shaft No. 1 was abandoned in the same way as shaft No. 2, the excavations being all removed by a side cut out of the open cutting. Very little trouble was caused by water. In the south end, an open drain sunk below formation was all that was necessary, and in the north end, where the work was with the gradient, a 5-inch special pump, placed at the shaft, was found to be amply sufficient. Yard wagons, drawn by horses on a 3-foot gauge railway, were used in all cases for removing the excavations. Much delay was caused owing to very soft shale and soft backs being encountered

between the harder rocks, where large masses were constantly dropping from the roof and sides. Lining to the extent of 1,300 lineal feet had to be put in to make these parts secure. But for this and other occasional stoppages, the tunnel would have been completed sooner. A great variety of rock was found in the tunnel, hardly a week passing without a change being experienced, the material ranging from the softest shale to the hardest of whinstone. The conglomerate was undoubtedly the worst to work, requiring, as it did, 28 holes bored in the face about 3 feet 6 inches deep, and giving a round of only 2 feet 6 inches. It was found quite impossible to anticipate the rock which had to be gone through, by that which appeared on the surface. With the rock drills an average of 21 holes was bored in the face, each about 5 feet deep. The order of firing was, centre holes, sides, top, after which the excavations were removed and the bottom holes fired. The length of time taken to bore the face depended entirely on the nature of the rock. It ranged from four to twelve hours. The working pressure on the air receiver was from 60 lb. to 80 lb. Experiments were made from time to time with various explosives, but it was found that Nobel's gelignite was most suitable. Sufficient air passed through the machines whilst working to thoroughly ventilate the tunnels, and no additional machinery was required for this purpose. The air was conveyed into the tunnel through 4-inch malleable iron pipes, this diameter being quite sufficient for all purposes. Showman lamps and paraffin candles were used in the place of tallow candles, and were found to be more satisfactory in every way.

The next tunnel in point of size on this contract was the Coire Eirigh, 2,035 yards long (fig. 2), through a ridge of slaty rock attaining 480 feet in height. The south end was started in May 1888, and the north end in September of the same year. Both ends were driven by hand for some 10 chains, after which the Hirnant drills were put in. In the south end the rock consisted largely of good hard slate in thin beds standing on edge. Undoubtedly this was the best working material that was found in any of the tunnels, and in several cases the rate of driving reached as high as 50 lineal yards per month. In the north end, however, the rock was of a

much harder nature, and the best speed was reduced to about 44 lineal yards. A junction was effected in January 1891.

The Meadhonach Tunnel, the next on the line of the aqueduct, is 610 yards long, but through very hard material; and after 13 chains had been driven in the south and 2 chains in the north end, it was found necessary to employ drills, which were accordingly placed in the north face in September 1890. A meeting was effected in August 1891. This tunnel has had to be lined for a distance of 321 yards.

In the Blairvaich Tunnel, 1,613 yards long, also shown on fig. 2, the south end was driven with drills, while for some time the north head was worked by hand labour; but, progress being slow, rock drills were ultimately used, and a meeting took place in July 1891. A great portion of this tunnel is in soft material, and 1,750 lineal feet of concrete lining had to be put in before the tunnel was driven through.

There are two small tunnels immediately south of the Kelty Tunnel (fig. 3, Plate XXIII.). One is the Corrie Tunnel, 440 yards long, which was commenced in May 1889 from the upper or north end, and was worked entirely by machine drills, with the exception of a few yards at the south end, the machines used being those described above. Several delays were caused by the soft nature of the rock, which required lining at once. A fair average driving was about 42 lineal yards per month, with two 10-hour shifts of six men each. The material was principally good working sandstone. The tunnel was finished in May 1890.

The other small tunnel, the Lossnaugh, extending to 476 yards, is interesting on account of its having been driven entirely by hand miners. It was started in July 1887 from the lower or south end, and was finished in October 1889, giving an average speed per month of 16 yards, with two 10-hour shifts of six men. The rock was good working sandstone. As the tunnel had very little cover, it was convenient to supply air by sinking 6-inch and 9-inch diameter bore holes from the surface at various points. In the cases of all these tunnels good meetings were effected.

These tunnels have all been lined as far as necessary, and the water has been running through the six miles of aqueduct since the end of

June 1892. Stop-plank chambers connect the old and new aqueducts at South Blairuskin (fig. 2), and divert part of the water from the old aqueduct into the new; at the south end it is passed again into the old aqueduct in the same way.

The Black Rigg contract was placed in February 1893 with Messrs. Morison & Mason. Mr. James Weddall is their engineer, and the Resident Engineer for the Glasgow Corporation, Mr. Robert F. Miller. There are three tunnels in this contract, which are shown on figs. 4 and 5; the most important of them is 2½ miles long. It is divided into lengths by three shafts, the average depth being 147 feet. The method of working closely resembles that which has already been described.

The Blane Valley contract (fig. 6, Plate XXIII.) was undertaken in March 1890 by Mr. James Young, whose engineer at the works for some years, Mr. R. Adam, has since been succeeded by Mr. James Russell. The resident engineer on behalf of the Corporation is Mr. A. Fairlie Bruce. The longest tunnel is that of Drumgoyne, which is 2,283 yards long, and was driven entirely from each end. At the northern end there was found very hard freestone with small whindykes from 3 feet to 10 feet thick, crossing the line of tunnel at right angles. Here the work was carried out, partly by hand, and partly with the Hirnant drill. The mean rates of progress were—from the north face ·89 lineal yard to 1·27 lineal yards per day, and from the south face 1·15 lineal yards to 1·83 lineal yards per day respectively. The former being driven against the gradient, water caused difficulty and delay. At the south end there was 'blaze' mixed with freestone rock, requiring that the lining should follow up the excavation at short intervals. The driving of the tunnel was completed on April 27, 1893, the error in lining being only ·25 inch.

The next longest tunnel on the section is that near Killearn, extending to 2,077 yards. Four shafts were sunk, the depth varying from 39 feet to 70 feet, and, in addition, driving was carried on from either end, so that there were in all ten headings; but as the material was red sandstone, the greater part requiring lining, only hand labour was used. The progress was at the rate of 6 yards per week at each face, six miners and two muck

fillers being employed in each of the two shifts, working each ten hours a day. The miners were paid, as a rule, 5*s.* 6*d.*, and the muck labourers 4*s.* 6*d.* per day. This tunnel is completed, the driving having occupied 159 weeks. The roof was very bad, and had to be supported with uprights and round timbers, with crossheads and bearing boards, and these were removed as the lining proceeded. The lining is as shown on fig. 11 in the worst places, and on fig. 17 it is shown as in the remainder of the tunnel.

The Lettre Tunnel, of 1,011 yards, was driven from either end without shafts and with hand labour. The material was principally red sandstone, and the progress was at the rate of nearly 6½ yards per week with two shifts. The time taken was ninety weeks. During the progress of the work there was a bad fall from the roof, the height of this fault being 20 feet. A concrete arch of 2 feet was thrown, and the space above filled with dry packing. This was done immediately after the fault discovered itself.

The Sauchie Tunnel, 882 yards long, through sandstone, varying between red and white, was driven with only two heads, from either end, and was completed in 480 working days by hand labour.

The last tunnel on the section, Ballewan, which is on the north slope of the valley, gave some little trouble because of the softness of the material. Indeed, this and the Killearn Tunnel were the only tunnels throughout the whole length of the aqueduct in which precautions had to be taken. In the first place, there were two angles on the line of tunnel, and for the purpose of alignment shafts were sunk at each, the depths being 65 feet and 69 feet, whilst there were observatories in line with either end of the tunnel. At the point of meeting, the difference was only 3 inches in line, and the level was absolutely correct. This was especially satisfactory in view of the existence of the angles. The tunnel is 1,689 yards in length, and was driven in 1,030 days, including delays due to lining the worst portions. The ventilation caused considerable trouble; two 6-inch bores were sunk to aid the fans. The driving, however, was only from two headings—one from either end. One of the shafts was used

only for raising the excavated material, and the other was not in use at all.

The material consisted of 'blaze' and sandstone, with two whinstone dykes, and it was found desirable to work in 12-foot lengths, timbering each length before proceeding with further excavation. In some parts the timbers had to be left in. It may be interesting to note here, that in some cases, where the ground was very wet, the contractors resorted to three short shifts, as the men could not work a longer shift. This was very expensive, as the men got a full day's pay for the eight hours' work.

Some particulars showing the average cost of driving a cubic yard of these tunnels are appended:—

Tunnel	Ballewan	Ballewan	Lettre
Material	Red Sandstone	Red Sandstone	Hard Red Sandstone with mica
Distance from mouth	730 yards	510 yards	465 yards
Labour	Manual	Manual	Manual
Excavated per man per day	·68 cubic yard	·74 cubic yard	·73 cubic yard
	s. d.	s. d.	s. d.
Foreman	0 5¾	0 6½	1 4
Miners	5 5	5 4½	4 9
Labourers—Men and boys	1 11	1 4½	1 5 Men 0 9 Boys
Horse and man	0 6¼	1 3	1 6
Total	8 4	8 6½	9 9
Explosives	0 10	1 5½	
Light	0 2	—	
Plant (wagons, rails, &c.)	0 6	0 6	
Total per cubic yard	9 10	10 6	

On this contract, careful data were taken as to the cost of excavating. In arriving at the results given above, the quantities were obtained from actual measurement, and the time occupied was noted by the inspector, the cost being based on the wages paid. In determining the cost of tools and plant, a fair percentage on first cost was taken, and the actual cost of blacksmith's labour included for sharpening, &c. In the case of the air-compressing operations, the coal consumed by the engine was estimated

by the inspector. The results by hand labour at three faces, and extending usually over a week, are given in the preceding table. These are for ten-hour shifts. The explosive mostly used was gelignite, but partly gunpowder also.

The extra cost in the second case is accounted for by the material being more 'dead' and not blowing so freely. Light was usually obtained from candles, but partly from naphtha lamps. In the second case, the cost under 'plant' is thus apportioned: blacksmith, $1\frac{1}{2}d.$; tools, $1\frac{1}{2}d.$; and $3d.$ for the remainder of the plant (wagons, rails, and shovels). The extra cost for horse and man in the second and third cases was due to a second horse being required to pull the wagons up a steep incline from the mouth of the tunnel to the spoil bank, whereas in the other case the inclination was towards the bank all the way. As to the third case, the large cost for foreman requires explanation.

Only four miners were engaged. Had there been six, a greater amount of material would have been excavated, and thus, the foreman's wage and other fixed charges would have been distributed over a greater number of cubic yards of excavated material. Nor was the full value of horse and man utilised, as in the first case. This, therefore, accounts for the greater cost for labour, other items being approximately the same.

The results of two investigations in the Drumgoyne Tunnel are interesting, since the data apply in one instance to ten-hour shifts, and in the other to eight-hour shifts. In both cases the work was carried on under conditions as nearly as possible similar, with Hirnant drills at the south heading, 800 yards from the outer face, in sandstone of medium hardness. About thirty holes were driven to an average depth of 3 feet 6 inches, and one round took about six to eight hours. The amount of explosive in a round averaged 4 lb., and the amount of material removed about 4 cubic yards. The average excavated per man per day in the ten-hours shift was 1·15 cubic yards, varying from 1·34 to ·95 cubic yards. In the eight-hours shift it was about ·82 cubic yard. The costs, as given in the table appended, again are per cubic yard.

As regards hand labour, a similar comparison might be made with the

figures given for the north face of the Ballewan Tunnel in a preceding table, but it may be sufficient to indicate the differences.

EIGHT- AND TEN-HOURS SHIFTS.—COST OF TUNNELLING WITH HIRNANT DRILL.

—	Ten-hours shift.		Eight-hours shift.	
Distance from mouth	420 yards Per cubic yard.		about 700 Per cubic yard.	
	s.	d.	s.	d.
Foremen	0	4	0	5½
Miners	3	7	4	6
Labourers and boys	1	1½	1	5
Horse and man	0	8½	1	5½
Total labour	5	9	7	10
Explosives	2	0	2	0
Light	0	2	0	2
Plant	1	0	1	0
Engine, driver, coal, &c.	0	9	0	9
Total	9	8	11	9

The average quantities of stores, used per cubic yard excavated in these and other tests, were as follows: Gelignite 1 lb., or gunpowder 4 lb.; fuse, ·2 hanks; caps, ·01 box; candles, ·10 packet; naphtha, ·10 gallon for the eight-hour shift. Foreman is 1*d.* per cubic yard less, miners 1*s.* 0½*d.* more, labourers 2¾*d.* more, horse and man 2¼*d.* less, making the labour cost in the eight-hours' shift 1*s.* per cubic yard more than when the ten-hours' shift was worked. With Hirnant drills it is about 2*s.* per yard more. This, of course, arises from the fact that the men are paid by the day. In other words, the attempt has been made to reduce the hours of labour of the miner in tunnels while at the same time maintaining the old rate of daily wage. This rate, it may be mentioned, is 5*s.* 6*d.* a day to miners and 4*s.* 6*d.* to labourers, whether working eight or ten hours. The result obtained, in this case at all events, is that the value of the work done per hour per man is the same on the eight- as on the ten-hours shift, so that, where the men are paid by the shift, the former is the less economical arrangement, and, as a rule, is only resorted to because twenty-four hours' work per day can be done in this way instead of twenty. Of course, if payment

is made by the hour, the result would not show the same discrepancy, and the comparison, however interesting, may not be conclusive in result. Certainly, it induced the contractors to abide by the two ten-hour shifts per day, and to discard the three eight-hour shifts. It is, however, important to note, that the cost of driving by the Hirnant drill by the ten-hour shifts is less than, in any case, by hand labour, notwithstanding harder material.

The last tunnel on the line of aqueduct was the Mugdock, and it was the first completed. It is at the south end of the Blane Valley syphon, and was bored and lined by Messrs. Morison & Mason, Glasgow. The Mugdock Tunnel will discharge into the service reservoir some 70,000,000 gallons of water per day. The first sod was cut on May 1, 1886; it was, in fact, the initial step of the whole work. The material in the tunnel was principally whinstone, some portions of which were very hard, but on exposure it withered, and hence arose the necessity for lining part of the tunnel. At first it was not intended to make an invert, but this also has been done almost entirely throughout the works, as it gives the water an easier flow. Work was commenced at both ends almost simultaneously, about four-fifths of the length being through whin-rock, and the remainder, at the southern end, being through soft material. The northern end was driven by machinery, almost from the commencement, two Hirnant drills having been used at the face, the pressure of air being 65 lb. to the square inch. The southern end, being in soft material, was driven by hand for 430 lineal yards. The soft material, known as volcanic ash, was dark brown in colour, close and compact when first exposed, but liable to wither on exposure, and had to be lined as the excavations progressed. This part having been finished and the solid rock reached, two Hirnant drills were also started, and the work carried on until the northern face was struck in July 1889. The air was compressed by machinery at the mouth of the tunnel, and led to the face by 6-inch cast-iron pipes. The exhaust air kept the atmosphere sweet. The average speed was 50 yards per month. In the face, eighteen to twenty-seven holes were bored, and the explosive mostly used was dynamite. The holes in the

bottom were fired first, and this relieved the material above and at the sides.

In February 1889, when 63 chains had been driven from the north end, operations were stopped and the remainder of the tunnel driven from the south, as greater progress was made from this end owing to the better drainage, due to the gradient running down from the face. The greater part is as shown in fig. 13, but for short distances the sides were also lined with concrete 1 foot thick, as in fig. 16. The side walls varied in height from 4 feet to the roof, which is 9 feet high. The length of the tunnel, with one side lined with concrete, was 295 feet, with two sides lined 537 feet, and with complete arching 1,562 feet.

The Mugdock Tunnel is 2,674 yards long, and runs parallel with the old aqueduct at a distance of 22 yards. At either end are stop-plank chambers, 32 feet by 18 feet, with a channel of concrete, 9 feet high and 8 feet wide, connecting the chambers of each aqueduct so that the water may pass through either. Indeed the water was passing through this section of the new aqueduct whilst the old Mugdock tunnel was under repair.

The new tunnel was first used in October 1890, when by a manipulation of the stop-planks the water of the existing aqueduct was diverted from the old to the new channel. The water, having a fall of 18 inches in the 2,674 yards, passed into the reservoir 45 minutes after being admitted, an evidence of the wisdom of having an invert, and of the smoothness with which this invert and the work generally had been done.

Messrs. Larmuth & Co.'s Hirnant machines, with rose-pointed drills, were used at all parts of the work on this and other contracts, and gave every satisfaction. The drills had cylinders $3\frac{1}{4}$ inches in diameter, and were mounted on McCulloch's carriage. The air-compressors were made by Messrs. Lamberton & Co., Coatbridge. An illustration of the drill, with the carriage on which it was mounted, is appended (fig. 18). On an ordinary bogie is a bedplate, attached to which is a vertical tubular bar having a screw thread formed upon it. The bar is so arranged that it may be raised or lowered by a screw nut, the outer periphery of which forms a worm wheel, geared with a worm on a horizontal shaft. Thus the vertical

bar can be tightened up against the roof, and rigidity secured. Upon the vertical bar are crossheads supporting horizontal tubular rack bars. This part of the apparatus is arranged to be raised or lowered by means of another screw nut, the exterior periphery of which forms a worm-wheel, geared with a worm fixed on a shaft supported in bearings on the cross-head. The rack bar is moved horizontally by a toothed pinion engaging

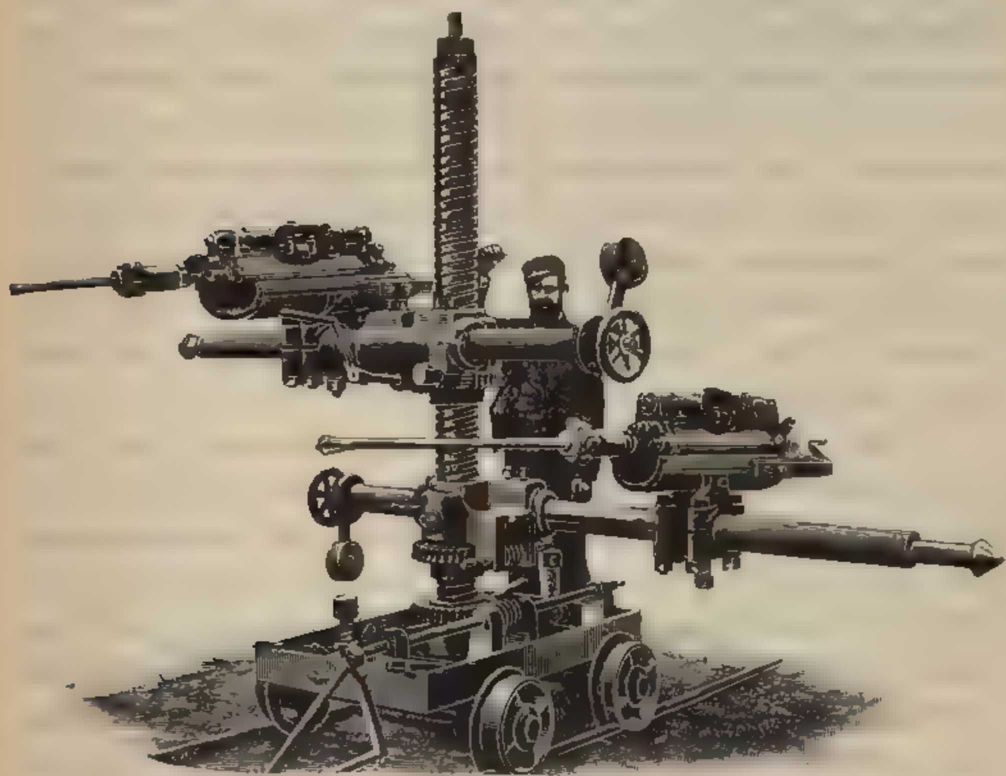

FIG. 18.

with the teeth on the bar, and is operated by a crank handle at the side of the crosshead. The horizontal bar is also moved in a circular direction by means of the crosshead. This rack bar is tubular and encloses a shaft screwed at one end, its screwed part working into a pivot for adjusting the bar when in a working position. At one end of the shaft is a self-acting weight, which acts upon the pivot when required to do so. The horizontal bar is thus kept in a rigid position whilst the drill is at work,

and at the same time it does not alter the position of the drill from the hole just started.

Many of the shafts sunk to facilitate the driving of the tunnels were really necessary for the subsequent ventilation of the aqueduct, and were consequently built to be permanent. Of these shafts, there are about five on the line of aqueduct, the greatest distance between any two being 3,575 yards. Fig. 32, Plate XXIV., shows a section of a permanent shaft. The over-all diameter is 8 feet, and the lining, which is of ashlar all round, reduces the internal diameter to 6 feet 6 inches. On the surface level there is built a hood, the diameter of which is 10 feet 6 inches. The walls rise to a height of 9 feet, and have a domed-shaped iron grating on the top. There is an entrance gate and a small platform two feet wide round the shaft, so that, in the event of repairs being required, a temporary platform may be arranged, and material lowered or raised by block and tackle. The top of the aqueduct is, of course, open at the foot of the shaft.

For the alignment of the tunnel, observatories were built on all altitudes, and on the slopes of hills on the line of the aqueduct, and the results obtained were highly satisfactory. The general arrangement of an observatory is shown on fig. 33. The chief feature is, of course, the centre pillar for the transit instrument. The pillars, the largest of which was about 31 feet high, are square, constructed of rough rubble in cement mortar, and all four sides have a batter of $\frac{6}{10}$ inch to the foot, the measurement at the top being in all cases 3 feet square. The coping stone is an ashlar block, 2 feet 6 inches square and 9 inches thick, chisel-drafted, and tooled on top to receive the transit instrument. The pillar is surrounded by walls 2 feet thick, of rubble masonry in lime mortar, carried up to within 4 feet of the height of the centre pillar, and surmounted by a superstructure of Baltic timber framing with weather boarding. The framing is secured by eight $1\frac{1}{4}$ tie rods, carried down to about 13 feet into the side walls below, and bolted to a series of bedded timbers in the outer walls. The purposes of the windows and semaphore signalling arrangements are evident. On the Black Rigg section of the work, the outer frame-

work was of wood, which was more conveniently obtained than stone. The outside timbers were 9 inches by 6 inches, the batter being $\frac{3}{4}$ inch to the foot. The bracing was by timbers 7 inches by 3 inches, and throughout $\frac{3}{4}$-inch bolts were used. The outside framing was sunk into a concrete bed, and stayed down to planking at the foot of it.

The methods adopted on the various sections for lining out the tunnels did not vary materially. In the case of the Ballewan Tunnel, there are two angles, which possibly invest this part of the work with special interest, and the system adopted by Mr. Adam may therefore be described. The centre lines were set out on the surface, large pegs being driven into the ground, and a nail put into the head to mark the centre. This was set out with a 7-inch transit theodolite. On this centre line the observatories were erected to such a height as to admit of a clear view from one to the other. The centre line was transferred from the pegs to the pillars of the observatories, the stands of the transit instruments being set up on this line. The telescope was taken to the highest observatory and placed on the stand. The stands on the lower observatory were then checked for line, by placing wooden rollers which were made to fit the Y's of the stands. The rollers had a small groove turned on them corresponding with the optical axis of the telescope. When the telescope was placed in the Y's of the stands, a small plummet was suspended from the groove on the roller for the convenience of sighting. On finding the stands correct (the lines as set out by the theodolite in no case differing from that of the transit instrument by more than $\frac{1}{2}$ inch), the foot blocks of the stand were run in flush with cement grout and with lead in place of cutting holes. In place of an ashlar cap on the top of some of the piers to set the stand on, concrete was used, and was in every way satisfactory. This was done to save labour, as a man was able to carry enough cement to do the work, and other necessary materials were found on the hillside.

There was no special difficulty in setting out Ballewan Tunnel, except that of working from a short base line. Shafts 12 feet by 6 feet were sunk at the angles; 12 feet being along the line of the tunnel, it was possible to get a 10-foot base line. The line was transferred below by suspending two

7-lb. plummets down the shaft by fine steel wires. The wires were placed exactly in line with that set out on the surface. A theodolite was set up below, in the tunnel, in line with the wires, the plummets being placed in buckets of water to stop vibration. The line was then carried forward into the heading with the theodolite, marks being made with a file on iron dogs fixed to the roof.

It may be mentioned that at convenient points along the line of aqueduct close by streams and rivers, and at the northern end of bridges, there are constructed chambers which serve not only the purpose of ventilating and affording access to the aqueduct, in the same way as the shafts, but have arrangements for overflows and drains. There are in all eleven chambers, which are illustrated by fig. 34, Plate XXIV., the views there given showing the actual structure north of the Blairgar Bridge, at 2 miles 35 chains.

Another arrangement which may be mentioned is the provision at various points of junction aqueducts connecting the new with the old aqueduct, stop-planks being also provided, so that the water may, when desired, be diverted from any one section of either aqueduct to the other. It has already been mentioned that the route for both water channels is practically the same, for although the new aqueduct strikes a more direct course, the greatest distance separating the two, at any point, is 1½ miles, and they frequently run parallel at distances of from 20 to 30 yards for considerable lengths, so that none of these connecting channels exceed 52 feet in length. Of these junction aqueducts there are in all eight. The general arrangement is shown by fig. 35, Plate XXIV.

THE SEVERN TUNNEL[1]

The Great Western Railway system west of Bristol was formerly separated, south of Gloucester, by the Severn and its estuary, from the

[1] This brief notice of the Severn Tunnel, from the pen of Mr. L. F. Vernon-Harcourt, M.Inst.C.E., is reprinted (by permission) from the *Proceedings of the Institution of Civil Engineers*, vol. cxxi. (session 1894–5, part iii.).

lines between Gloucester and the South Wales ports, as well as from the western lines between Hereford and North Wales, Liverpool, Manchester, and the north. This want of connection was only partially remedied by a steam ferry across the estuary of the Severn, from New Passage to Portskewett, with connecting branch lines, which involved transhipment of passengers and goods. A tunnel under the Severn estuary was, accordingly, proposed by Mr. Charles Richardson in 1871, to provide for through traffic, and was authorised in 1872; and the works were commenced by the Great Western Railway Company in 1873, by sinking a shaft, 15 feet in diameter and lined with brickwork, near the Monmouthshire bank of the Severn, to a depth of 200 feet. The site selected for the tunnel is a short distance below the ferry, and about two miles below the mouth of the Wye, where the width of the estuary at high tide is about $2\frac{1}{4}$ miles, and the main low-water channel is $2\frac{1}{2}$ furlongs wide, the maximum depth of the estuary at high water of springs at this place being 95 feet with a tidal rise of 37 feet. The strata traversed by the tunnel consist of conglomerate, lime-stones, carboniferous beds, sandstone, marl, gravel, and sand, having a considerable dip; and the least thickness of soil between the top of the tunnel and the deepest part of the channel is $44\frac{3}{4}$ feet. The total length of the tunnel is 4 miles 624 yards.

After the Monmouthshire shaft had been sunk, a heading 7 feet square was driven under the river, rising with a gradient of 1 in 500 from the shaft on the Monmouthshire shore so as to drain the lowest part of the tunnel. Near to the first, a second shaft was sunk and tubbed with iron, in which the pumps were placed for removing the water from the tunnel works, connection being made by a cross-heading with the heading from the first shaft. There was also a shaft on the Gloucestershire shore; and two shafts inland from the first on the Monmouthshire side, to expedite the construction of the tunnel. Headings were then driven in both directions along the line of the tunnel, from the four shafts; and the drainage heading from the old shaft was continued, in the line of the tunnel, under the deep channel of the estuary and up the ascending gradient towards the

Gloucestershire shore, till, in October 1879, it had reached to within about 130 yards of the end of the descending heading from the Gloucestershire shaft. During this period, though the work had progressed slowly, no large quantity of water had been met with in any of the headings, in spite of their already extending under almost the whole width of the estuary. On October 18, 1879, however, a great spring was tapped by the heading which was being driven landwards from the old shaft, about 40 feet above the level of the drainage heading ; and the water poured out from this land spring in such quantity that, flowing along the heading, falling down the old shaft and thus finding its way into the drainage heading and the long heading of the tunnel under the estuary in connection with it, it flooded the whole of the workings in communication with the old shaft, which it also filled within twenty-four hours from the piercing of the spring. Under these circumstances, the directors appointed their consulting engineer, the late Sir John Hawkshaw, to be engineer-in-chief of the works; and the contract for the completion of the tunnel was entrusted to the late Mr. T. A. Walker.

To obtain increased security against any influx of water from the deep channel of the estuary into the tunnel, the proposed level portion of the tunnel, rather more than a furlong long under this part, was lowered 15 feet by increasing the descending gradient on the Monmouthshire side from 1 in 100 to 1 in 90, and lowering the proposed rail-level on the Gloucestershire side 15 feet throughout the ascent, so as not to increase the gradient of 1 in 100 against the load. A new shaft, 18 feet in diameter, was sunk slightly nearer the estuary on the Monmouthshire shore than the old one; two shafts also were sunk on the land side of the great spring, for pumping purposes ; and additional pumping machinery was erected. The flow from the spring into the old shaft was arrested by a shield of oak fixed across the heading; and at last, after numerous failures and breakdowns of the pumps, the headings were cleared of water, after a diver, supplied with a knapsack of compressed oxygen, had closed a door in the long heading under the estuary; and the works were resumed nearly fourteen months after the flooding occurred. The great spring was then shut

off from the workings by a wall across the heading leading to the old shaft; and, owing to the lowering of the level of the tunnel, a new drainage heading had to be driven from the bottom of the new shaft at a lower level, which was made 5 feet in diameter and lined with brickwork, whilst the old drainage heading was enlarged to 9 feet in diameter, and lined with brickwork, so as to aid in the permanent ventilation of the tunnel. The lowering of the level, moreover, converted the bottom tunnel headings into top headings, so that along more than a mile of the tunnel the semicircular arch, 26 feet in diameter, was built first, and then, after lowering the headings, the invert was laid and the side walls were built up. Bottom headings were driven along the remainder of the tunnel, and the work was expedited by means of break-ups. Ventilation was effected in the works by a fan 18 inches in diameter and 7 feet wide, fixed at the top of the new deep shaft; the rock was bored by drills worked by compressed air; the blasting was eventually effected exclusively by tonite, owing to its being freer from deleterious fumes than any other explosive; and the workings were lighted by Swan and Brush electric lamps. The tunnel is lined throughout with vitrified brickwork, between $2\frac{1}{4}$ feet to 3 feet thick set in cement, and has an invert $1\frac{1}{2}$ feet to 3 feet in thickness; the lining was commenced towards the end of 1880, the headings under the river were joined in September 1881, and the last length of the tunnel, across the line of the great spring, was completed in April 1885.

Water came in from the river through a hole in a pool of the estuary, close to the Gloucestershire shore, in April 1881, during the lining of a portion of the tunnel, but fortunately before the headings were joined. This influx was stopped by allowing the water to rise in the tunnel to tide-level, to prevent the enlargement of the hole, which was then filled up at low water with clay, weighted on the top with clay in bags. The great spring broke out again in October 1883, and flooded the works a second time; but within four weeks the water had been pumped out, and the spring again imprisoned. During this period an exceptionally high tide, raised still higher by a south-westerly gale, inundated the low-lying land on the Monmouthshire side of the estuary, and, flowing down one of the

inland shafts, flooded a section of the tunnel, but the pumps removed this water within a week.

In order to construct the portion of tunnel traversing the line of the great spring, the water was diverted into a side heading, below the level of the tunnel, leading to the old shaft, whence it was pumped, and the fissure below the tunnel was filled with concrete, over which the invert was built. An attempt to imprison the spring, on the completion of this length of tunnel, having resulted in imposing an excessive pressure on the brickwork, leading to fractures and leakage, a shaft, 29 feet in diameter, was sunk at the side of the tunnel at this point in 1886, and pumps were erected powerful enough to deal with the entire flow of the spring.

The tunnel was opened for traffic in December 1886, and gives access to a double line of railway connecting the lines converging to Bristol with the South Wales Railway and the western lines. The pumping power provided at the shaft connected with the great spring, and at four other shafts, is capable of raising 66,000,000 gallons of water per day, the maximum amount pumped from the tunnel being 30,000,000 gallons a day. The ventilation of the tunnel is effected by fans placed in the two main shafts on each bank of the estuary, and the fan in the Monmouthshire shaft is 40 feet in diameter and 12 feet wide. The tunnel gives passage to a large traffic, numerous through trains between the north and south-west of England making use of it.

A very full and graphic account of the progress of the tunnel works, and the difficulties encountered, was published by the late Mr. T. A. Walker, soon after the opening of the tunnel for traffic.[1]

[1] *The Severn Tunnel; its Construction and Difficulties*, 1872-1887. Thomas A. Walker, 1888. Brief accounts of the works are also given in a paper on *The Severn Tunnel Railway*, J. C. Hawkshaw, British Association Report, Montreal, 1884, p. 884; and in *Achievements in Engineering*, L. F. Vernon-Harcourt, 1891, pp. 96 and 100-6.

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PLATE XXIII.

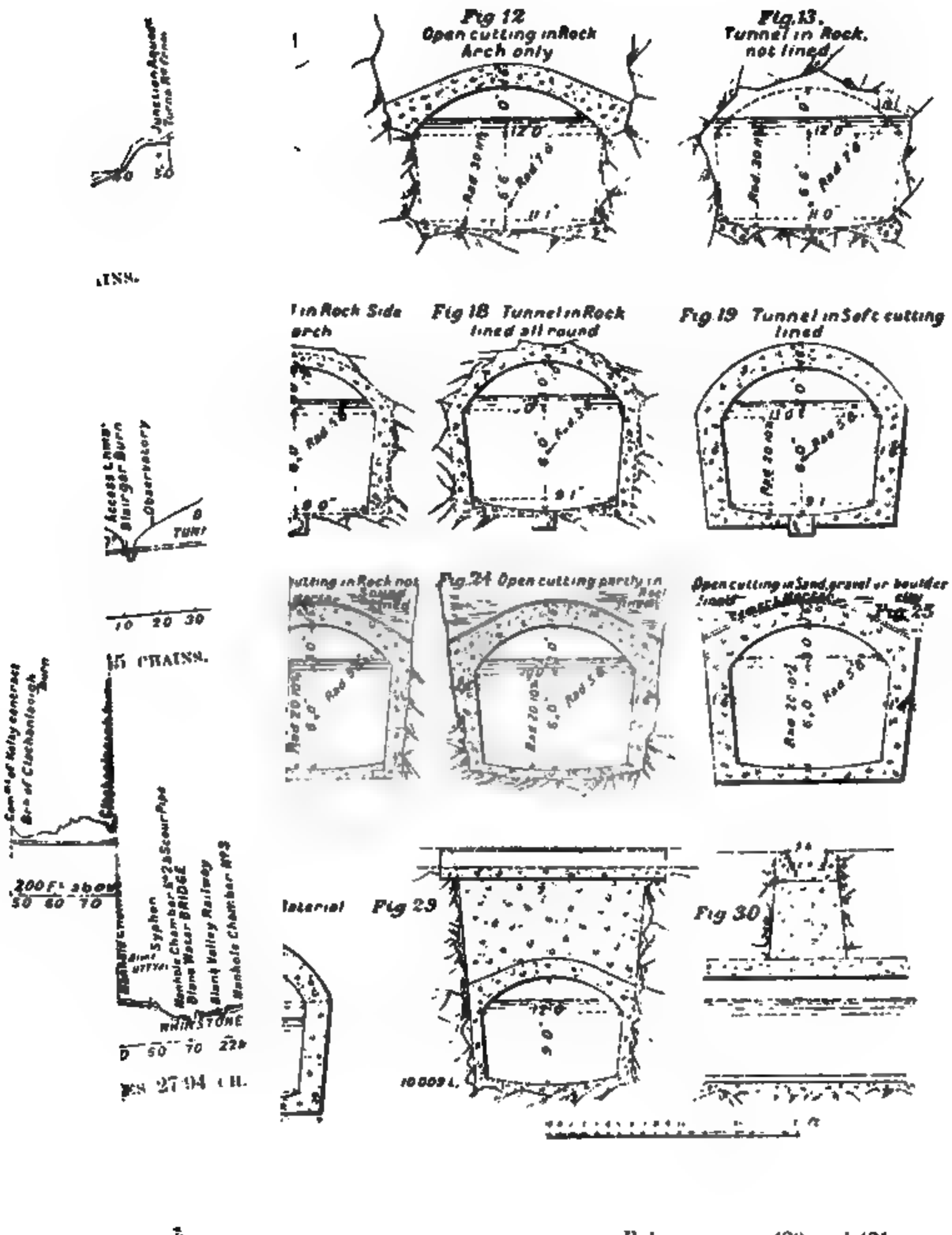

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PLATE XXIV.

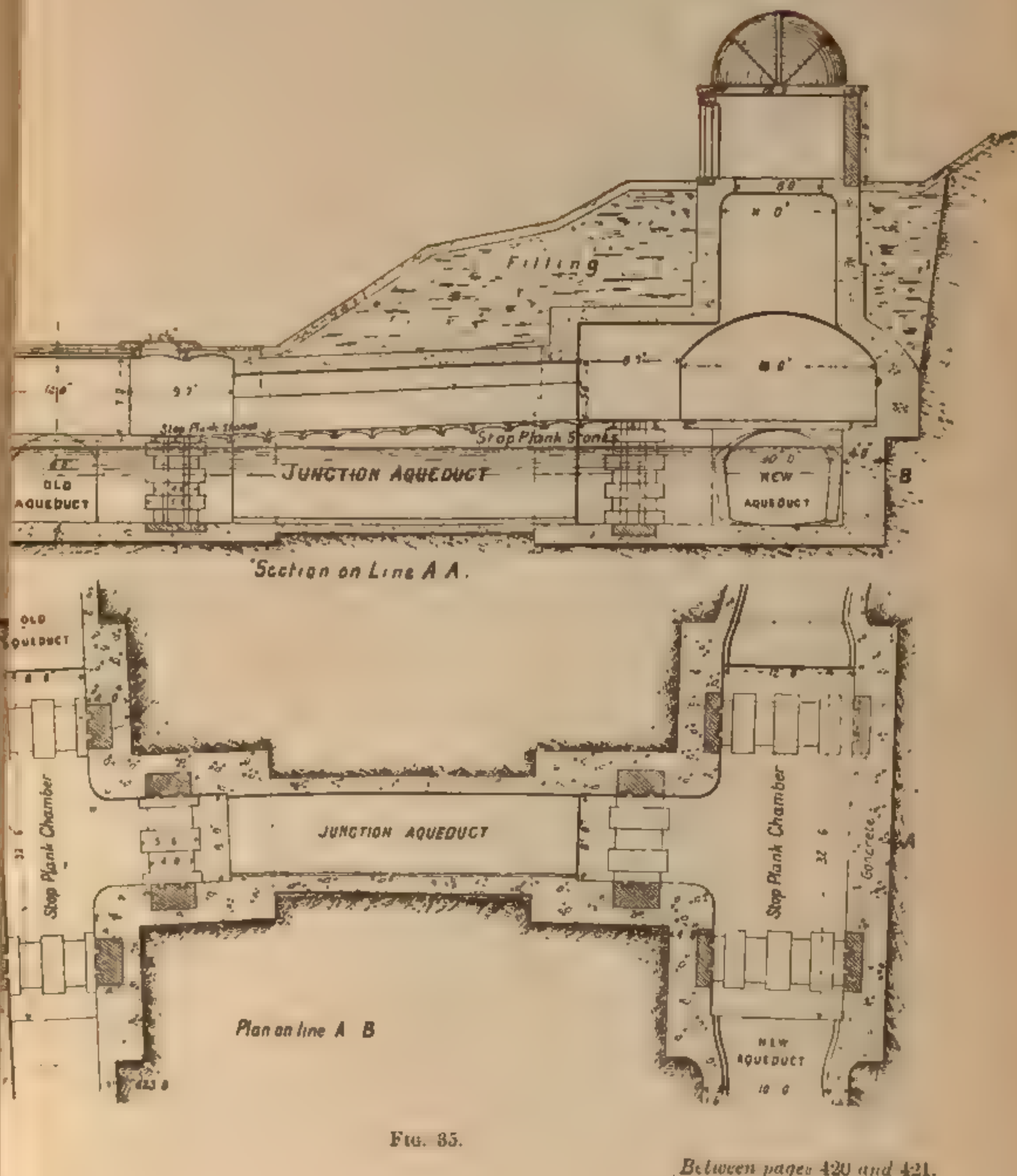


FIG. 35.

Between pages 420 and 421.

CHAPTER XXX.

TUNNELLING THROUGH HARD ROCK (CONTINUED).

THE SIMPLON TUNNEL.

A Company has been formed to construct a tunnel through the Pennine Alps under Monte Leone, and a report has recently been issued in which the difficulties which are expected to be encountered are mentioned, and also the manner in which it is hoped to surmount them.

Several projects have been launched, from time to time, for connecting the railway which runs from Geneva to Brigue with that which starts from Domo d'Ossola on the main line from Turin to Milan. One of these projects embraced the construction of a tunnel at least 10 miles long, but starting practically at the level of the lines which it is intended to connect. The railway company decided that, in order to compete with the neighbouring Alpine lines, a project on this basis must be adopted, and it eventually decided upon the line about to be described.

In this scheme the tunnel starts half a mile above the new station at Brigue on the left bank of the Rhone, and passes through the mountain in a north-westerly direction. Its southern extremity is on the left bank of the Diveria, and its length will be 12 miles 460 yards. At the northern end it is 2,255 feet above sea level, at the centre 2,314 feet, and at the southern end 2,080 feet. The frontier line between Italy and Switzerland crosses the axis of the tunnel at right angles, near the centre, and at this point the tunnel is 7,000 feet below the surface of the ground (see fig. 1). The altitude of the northern end was fixed by the high-water mark of the Rhone, whilst at the southern end the level is the same as the existing road. The position of the ends being fixed, and the southern end being 175 feet

lower than the northern, it was decided that the latter should have the least incline which would permit of the water running off freely, and a gradient of 2 per mil was chosen. It was then discovered that the southern end would have an inclination of 7 per mil.

The tunnel will commence and end with short curves, the radius of that on the north being 365 yards, and that on the south 328 yards. For 11 miles and 1,640 yards it will be in a straight line. The length of the northern section, 2 per mil incline, will be 5 miles 1,100 yards; of the southern, 7 per mil, 6 miles 563 yards; and the intermediate 547 yards

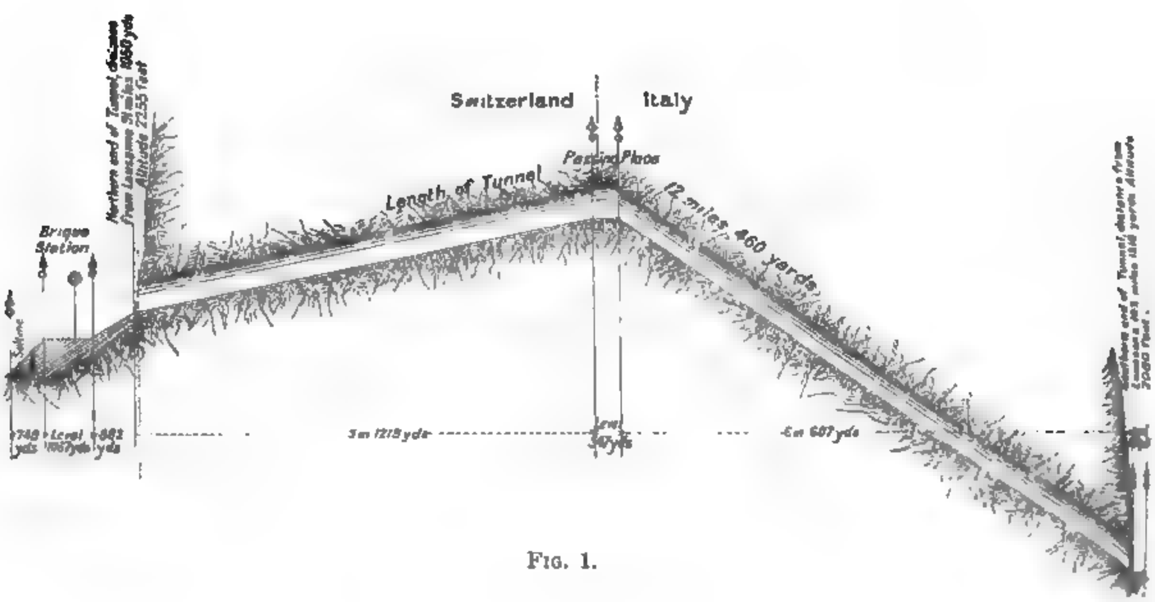


FIG. 1.

will be level. A table is appended giving the following particulars respecting the different tunnels which pass through the Alps.

	Mount Cenis.	Gothard.	Arlberg.	Simplon.
	miles yards	miles yards	miles yards	miles yards
Length of tunnel	7 1,734	9 549	6 640	12 460
Altitude, northern or eastern end	3,766 feet	3,639 feet	4,274 feet	2,255 feet
„ southern or western end	4,164 „	3,757 „	3,998 „	2,080 „
„ highest point	4,248 „	3,788 „	4,300 „	2,314 „
Maximum gradient in tunnel per mil.	22	5·82	15	7
„ altitude of ground above axis	9,676 feet	9,386 feet	6,662 feet	9,319 feet
Maximum thickness of mountain above tunnel	5,428 „	5,598 „	2,362 „	7,005 „
Maximum temperature of rock	85° F.	87° F.	65° F.	104° F.

Cross-sections.—The Simplon Tunnel will differ from all others which have been made through the Alps, in that it will eventually consist of two parallel tunnels 56 feet apart, each being laid for a single line of rails. Each tunnel is to have a minimum sectional area of 250 square feet in the clear. The width in the clear is to be 14 feet 9 inches at the level of the sleepers, and 16 feet 5 inches at 6 feet 6 inches above them. The height from the top of the sleepers to the key of the arch is to be 18 feet. As will be seen by reference to fig. 2, Plate XXV., five different cross-sections have been designed, to be adopted according to the nature of the ground which is being traversed.

These sections are as follow: (A) in compact rock with regular strata, no lining required; (B) in rock requiring a light lining, and, where the strata are irregular, side walls and arch in ashlar, 15 inches thick; (C) in ground where there is a medium pressure, side walls in ashlar, arch in dressed stone 20 inches thick; (D) in ground where there is a strong vertical pressure, side walls in coursed masonry, dressed stone arch, 24 inches thick; (E) in ground which is in a state of decomposition and where there is strong lateral pressure, side walls in coursed masonry, an invert 16 inches thick, and arch 24 inches thick in dressed stone.

At intervals of 110 yards, on one side only, there will be refuges 6 feet 6 inches wide by 7 feet 6 inches high. At every 1,100 yards, in place of these niches, there will be a room 9 feet 10 inches wide and deep, and 10 feet 2 inches high, serving for signals and lamps. Besides these, four larger rooms will be constructed, to serve as stores for platelayers' tools, &c. These will be placed at equal distances apart, and will be 13 feet 2 inches wide, 10 feet 2 inches high, and 19 feet 8 inches deep. The two headings are to be 12 feet 1½ inches wide by 12 feet 7½ inches high, above the sleepers. The parallel gallery will be lined wherever it is considered necessary. It will contain the principal channel for carrying off the water, and all the drainage from the main tunnel will be led into it. To allow trains to cross, there will be a siding a quarter of a mile long in the middle of the tunnel.

Cost.—The contract for carrying out the work was signed on

September 20, 1893, with Messrs. Brandt, Brandau & Co., who have agreed to complete the construction for the following amounts:

(1) Preliminary construction	£280,000
(2) First single line tunnel, with parallel gallery	1,900,000
(3) Completing the second single line tunnel	600,000
Total for two single line tunnels complete . .	£2,780,000

These prices, however, do not include the purchase of land for building; the materials for the permanent way of the two tunnels; or the ballasting of the second tunnel. The first tunnel is to be complete in 5½ years, but the time for the completion of the second tunnel is limited to four years from the time of its commencement.

The following has been adopted as the normal rate of progress for the execution of the work:

—	Main and parallel galleries.		Upper headings.		Opening out to full size.		Masonry.	
	miles	yards	miles	yards	miles	yards	miles	yards
1st year	1	318	—	1,641	—	985	—	219
2nd „	2	524	2	417	2	417	2	308
3rd „	2	964	2	746	2	636	2	746
4th „	2	1,511	2	1,511	2	1,402	2	1,292
5th „	3	298	3	408	3	626	3	736
Last 6 months	—	365	—	1,674	-	1,674	1	679

System of Construction: Ventilation.—In all previous projects for the construction of a tunnel under the Simplon, great difficulties were anticipated on account of the subterranean heat. But the method of construction and ventilation proposed to be adopted is quite new, as, instead of making a single tunnel for the two lines of rails, two headings will be driven simultaneously, their centres being 56 yards apart. Every 220 yards these headings will be connected by transverse passages, as shown in figs. 3, 4, 5, 6, Plate XXV., and figs. 7 and 8, p. 425. Of the two headings, No. I., fig. 9, will be opened out to the full section as the work advances; but tunnel II., fig. 10, will only be finished when the traffic renders it necessary to lay a double set of rails throughout.

In constructing tunnel No. I., the advance heading will be made on the base, shafts being raised from time to time to the roof, and headings driven from these in both directions. Finally, the tunnel will be enlarged to the full size, in the usual way, and finished.

Mechanical Perforation in Headings.—Headings I. and II., figs. 9, 10, 11, will be started simultaneously, with three or four Brandt's rotary hydraulic drilling machines working at each face, the motive power being furnished by two 4-inch mains. For the first half of the north end, whilst penetrating the schist, it is proposed to use a pressure of 1,000 lb. to the square inch;

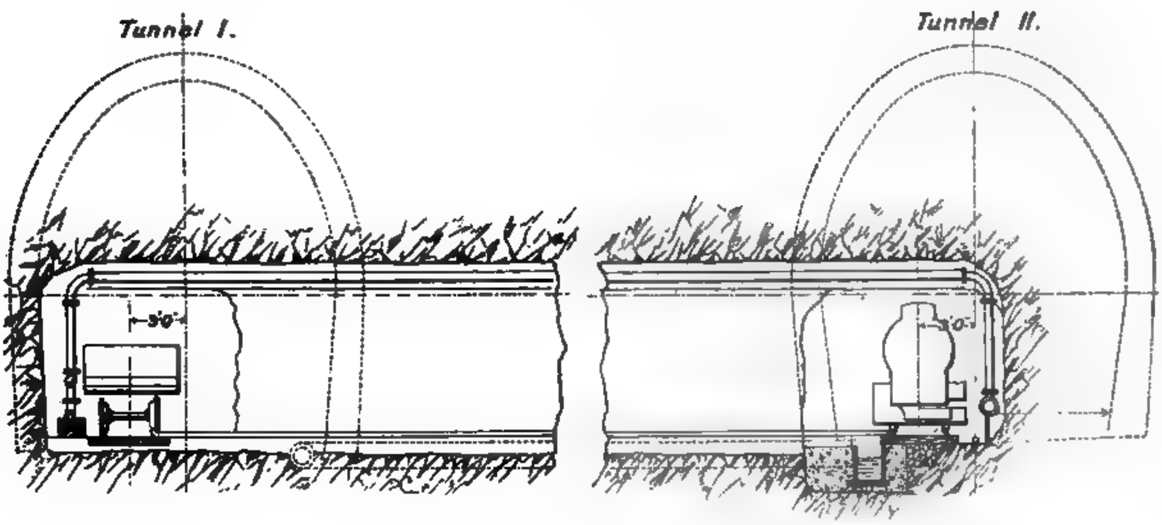


FIG. 7. FIG. 8.
SECTION THROUGH TRANSVERSE GALLERY.

but for the second half, and for all the southern end, where gneiss has to be penetrated, the pressure will be 1,500 lb. In addition to the six or eight machines in these headings, there will be four on each side for the upper headings and cross galleries. These twelve machines will use 4 gallons of water per second, at a pressure varying from 1,000 to 1,500 lb. In hard rock, twelve to fifteen holes, 2¾ inches in diameter and about 49 inches deep, will be needed; in schist, eight to ten holes of the same diameter and about 55 inches deep. Two months after work is commenced the rock drills can be started. It is estimated that, during two months of hand drilling, about 66 lineal yards will be excavated at each end; during the ten

succeeding months at 5 yards a day, 1,500 yards at each face; and to complete the work in the remaining forty-nine months, a daily average progress of $6\frac{1}{2}$ yards will be required.

Removal of the Rubbish.—Though various plans have been tried from time to time for performing this indispensable operation, nothing has been found to be better than the old system of loading up by hand direct into the trucks in which the spoil is to be removed. The difficulty hitherto has been that the material falls in front of the face, and thus fills the space which is required to be occupied by the drilling machines. The contractors propose to get over this difficulty by using a machine which will push the material blown down, quickly to the right and left.

The shafts and upper headings in tunnel No. I. will be commenced in each 220-yard section, as soon as the cross gallery for each section has been opened, and the current of air has begun to pass through it. Hand or machine drilling respectively will be employed, according to the nature of the material to be acted upon. As soon as one heading reaches the next, the full section will be opened out, and the masonry put in without delay.

Ventilating and Cooling.—The process of ventilating has already been explained; it is intended to pass through heading No. II., 1,750 cubic feet per second, at a velocity of 20 feet. This quantity of air should be sufficient to render any other cooling arrangements, either in the headings or by the masons, unnecessary. But the temperature can and will, if necessary, be further lowered by the use of water sprays in the transverse galleries. A pressure equal to $19\frac{1}{2}$ inches of water will be requisite to drive 1,750 cubic feet of air through a heading six miles long, and, taking the effective duty of the fans to be ·65 per cent., a force of 500 horse-power will be wanted to provide this volume of air. Two fans, 18 feet diameter, will be erected at each end of the tunnel and coupled directly to the turbines. These fans will be arranged so that, coupled one behind the other, they can force 1,750 cubic feet of air at a pressure of $19\frac{1}{2}$ inches, or, coupled side by side, they can pass 3,500 cubic feet at $9\frac{3}{4}$ inches pressure.

The cooling water main will be laid in tunnel No. II., branches being laid through the transverse galleries as the work advances.

Transport.—Lines of 2-feet 7½-inch gauge and with 40 lb. rails will be laid in each heading, and there will be branches at each cross gallery. Special locomotives will be built for service inside the tunnel. These will have extra large boilers, so that there may be no need for stoking inside the tunnel, and will weigh, in working order, 16 tons each. They are to be capable of going round a curve of 50 feet radius. The trucks will have a capacity of 70 cubic feet, and seats for three men back and front.

Ventilation after completion.—The tunnel being twelve miles long, it will be necessary to arrange an artificial system of ventilation.

In burning coal various injurious gases are produced. Of these the most important is carbonic acid, and then follow carbonic oxide and sulphurous acid. These two latter gases are, however, as a rule, produced in comparatively small quantities, and the sulphurous acid is, owing to the humid nature of the air of tunnels, rapidly oxidised and precipitated on the walls.

When the tunnel is completed and being used, the same apparatus will be used for ventilation as during construction. Two fans will be set up at each end of the tunnel, which can either exhaust the air from, or force air into the tunnel as may be requisite. The ventilation can be effected in three different manners. Firstly, air can be passed through the parallel heading into the tunnel; secondly, 1,750 feet of air can be forced into the north end of the tunnel, and pass through it from end to end; and thirdly, the ventilation can be done in the opposite direction from south to north.

After due consideration it has been decided that the following arrangements for ventilation shall be adopted:

(1) Whilst No. I. tunnel only is open, 1,750 cubic feet of air shall be introduced into the north end per second, the entrance at that end being closed by a door.

(2) When both tunnels are at work, 1,750 cubic feet of air will be forced into the northern end of No. I. and the same quantity into the south end of No. II.; consequently, the current of air in each tunnel will travel in the same direction as the trains. There will be doors at the northern end of tunnel No. I. and the southern end of tunnel No. II. It is from reasons

of economy that it has been decided to ventilate in the same direction that the trains travel. It has been observed that even in short tunnels the trains, in passing through, draw a considerable quantity of air after them, so that, by forcing air after the train at a greater speed than it would otherwise travel, the fan returns to the train the work done in pushing the air before it. This represents a saving in fuel which, it may be added, is increased in proportion to the increased speed of the trains.

Calculations have been made to show that, after allowing for the friction against the sides of the tunnels, a pressure of $2\frac{1}{4}$ inches of water is sufficient to force the requisite quantity of air through the tunnel. As the power of the fans used during construction was greater than this, they should be ample for ventilation after completion. There will be two fans and two turbines at each end, but it will only be necessary to use one. Efficient ventilation could thus be maintained from one end of the tunnel, should the whole of the machinery at the other end require to be stopped for any reason. Thus, for instance, should the power house at the southern end be not available for working, one fan at the northern end would force air into tunnel No. I. whilst the other fan aspired it from No. II.

Noxious Gases produced by Locomotives passing through the Tunnel.—From a series of experiments, the company have found that, besides other gases, one pound of coal, when completely burnt, produces 26 cubic feet of carbonic acid. On this basis they have made a series of calculations to ascertain the quantity produced by each train—express, ordinary, or goods—and going from south to north, or from north to south. The results of these calculations have been applied to the varying conditions under which the tunnel may be worked. Firstly, when one tunnel only is open for traffic. Here the maximum daily service is taken to be four express trains, eight ordinary, and thirty-six goods trains, or a total of 48 trains, 24 each way. On this the conclusion is arrived at, that the greatest excess of carbonic acid over that ordinarily contained in the atmosphere may amount to 4 per mil in the southern half of the tunnel, and may reach as much as 8 per mil near the north end. When both

tunnels are used, and each one ventilated in the direction of the trains, the air will become more impure in tunnel No. II. than in tunnel No. I. But upon the supposition that a goods train passes through this tunnel every thirty-five minutes, the excess of carbonic acid in the air, which will be at its worst near the northern end, will be only about 9 per mil. It is, therefore, safe to assume that never, under any circumstances or in any part of the tunnel, can it reach the limit of 1 per cent.

TUNNEL AT NIAGARA FALLS.

A company, styled the Niagara Falls Water Power Company, has been formed in the United States for the purpose of utilising the enormous water-power developed by the Falls; and in the course of the work entailed by the execution of this project, a 'tail-race' tunnel through solid limestone rock has had to be constructed. The water is conveyed to this tunnel by means of a canal which starts at a point $1\frac{1}{4}$ miles above the Falls. It is 188 feet wide where it leaves the river, narrowing subsequently to 116 feet, and is 17 feet deep. The depth of the water is 12 feet.

The construction of the tunnel was commenced by the contractors, Messrs. Rogers & Clement, in the fall of 1890. The rock to be operated upon was a limestone with slaty seams, which leaked to a most unprecedented extent and seriously impeded the progress of the work. The water poured through the workings in many places, forming miniature cascades, and it was owing to Mr. Clement's skill, and the assistance of several very large pumps, that it was kept under control. Although the rock seemed very hard, it became disintegrated very rapidly when exposed, and frequently fell in large masses, so that the tunnel had to be timbered during construction and lined with brick after completion.

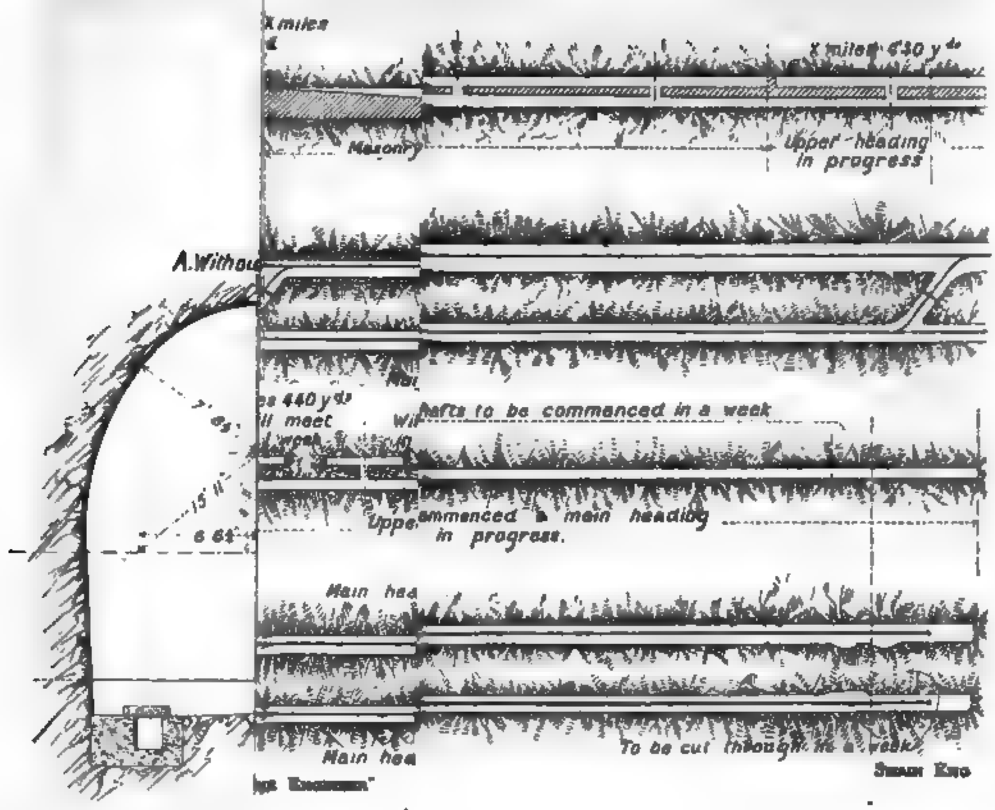
Three shafts were sunk in prosecuting this enterprise. The first was at the portal, and was sunk to a depth of 260 feet. The second shaft was 2,600 feet distant, and was also sunk to a depth of 260 feet. The third shaft, 2,600 feet farther away, was sunk 196 feet; and this left 1,800 feet

from the last shaft to the wheel-pit. As soon as the shafts were started, the water came in rapidly. This flow, at the rate of 107 feet in Shaft 1, rose to 800 gallons per minute; and in Shaft 2, at 70 feet, it was 600 gallons a minute. The water was collected in two sump-holes, sunk in places made by drifting 15 feet each side of the shaft. By stretching canvas behind the tunnel timbers, the water was collected in wooden troughs and thence carried to the sumps. In driving the headings, of which there were five, the full width of the tunnel was opened, and then two benches were made, and the heading was driven by the centre-cut system. Four to six drills were used, and the rock was blown down by dynamite. The tunnel timbering was put in as the heading advanced.

After clearing the heading, two sills were laid and rib timbers erected and braced by struts. The second bench was then removed, the sills being supported by posts. If the rock broke away, the posts were put in under the sills.

In the construction of this tunnel 13,600,000 bricks were used and 45,000 barrels of giant Portland cement. Seventy-five bricklayers were employed and 130 helpers. 110,000 bricks were laid in ten hours.

The tunnel was driven ahead with great rapidity, and was completed in twenty-three months' actual time, but a time correction of at least two or three weeks should be made in order to arrive at the net time, and it is believed that this is one of the most rapid instances of tunnel driving on record.



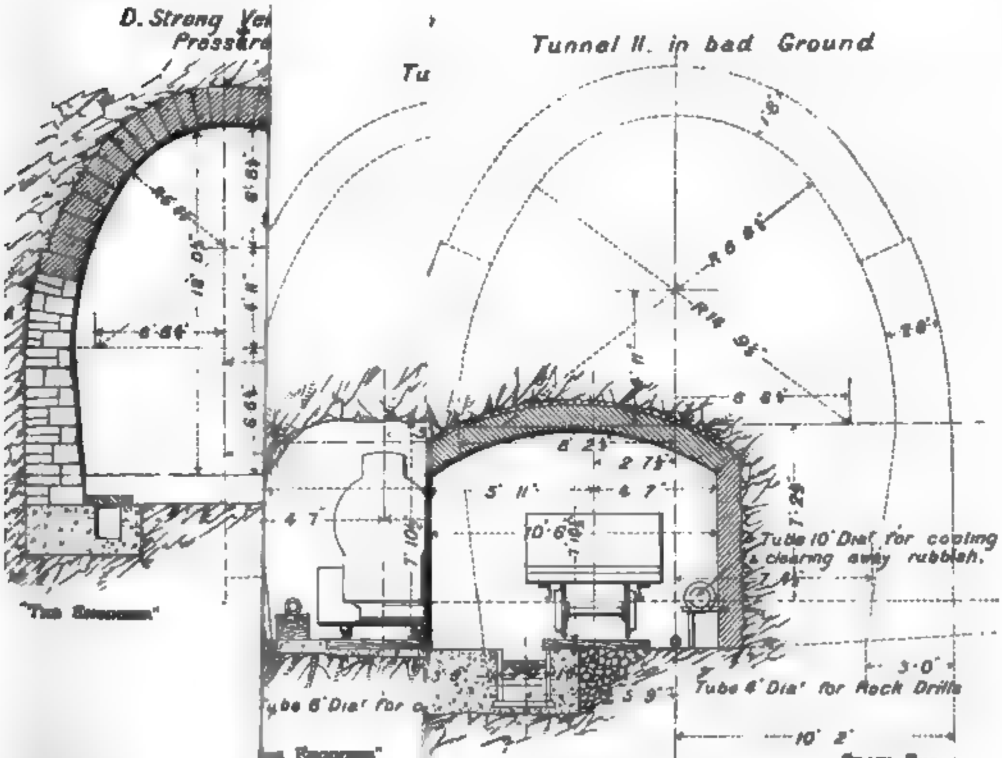


Fig. 11.

[*Between pages 480 and 481.*

CHAPTER XXXI.

TUNNELLING THROUGH SOFT ROCKS.

THE TEQUIXQUIAC TUNNEL FOR THE DRAINAGE OF MEXICO CITY (THROUGH SANDSTONE).

THE object of this tunnel, and of the canal which forms part of the scheme now in progress, is to control the water in the lakes in the vicinity of Mexico, and to afford an outlet for the storm waters and sewage of the city. Both works are approaching completion, the contractors for the canal being Messrs. Pearson & Son, and of the tunnel Messrs. Read & Campbell.

The original scheme was proposed early in the seventeenth century by the Viceroy Martin Enriquez. It consisted of a tunnel fully 4 miles long, 11½ feet by 14 feet, through the hill of Nochistengo to the valley of Tula, beyond the hills which surround the valley on the north-western side. This work was performed by 470,000 Indians in two years; but the tunnel was neglected, became choked up, and the city was inundated owing to the walls being inadequate. The tunnel, however, was subsequently opened up again, and thus was formed the cut, resembling a natural gorge, through which the Mexican Central Railway runs. The cut in question is 13 miles long, and varies in width from 280 feet to 360 feet, with a depth of from 150 feet to 200 feet. The relief, however, thus afforded was but partial, as the cut only takes the drainage of one, out of the six lakes, the highest; and almost the entire valley, which has an area of 1,660 square miles, was still without natural outflow. The city was, therefore, not infrequently inundated during the wet season.

The tunnel, which is about to be described, has been driven through

another of the mountains, and will, it is expected, remove all similar difficulties. This scheme is a modification of one proposed many years ago by Francisco Gray, an eminent Mexican engineer. The drainage of the northermost lake, Zumpango, the one at the highest level, passes through the cut already described; the lake at lowest level is Texcoco, which also receives the drainage of the city. The annual rainfall is 20 inches, equivalent to 155,000,000,000 cubic feet of water. The evaporation is very rapid; but the rain falls within a short period, and thus some 28,250 million cubic feet of water reach the lakes, in addition to the quantity which passes through the northern cut.

The canal starts at the city gates, and is 22 miles long to the new tunnel, which pierces the northern boundary of the valley, and discharges the water into the valley of the Tequixquiac. The construction of the canal involved the excavation of some 425,000,000 cubic feet of material, which has been removed by large steam dredgers, and is now nearly complete. The canal varies in depth from 17 feet to 65 feet, with slopes at an angle of 45 degrees. Numerous subsidiary works, in connection with the crossing of railways and high roads, and the making of sluice gates, enter into the project, and increase the already numerous difficulties incidental to the excavation of this immense canal.

The tunnel involved many interesting problems, the solution of which engaged the attention of Mr. J. Fletcher Toomer, A.M.I.C.E., the engineer for Messrs. Read & Campbell, the contractors. The length of the tunnel is $6\frac{1}{4}$ miles, and it has been constructed from designs supplied by the Government engineers. The gradient is 1 in 1388·88. The section is as shown in fig. 1, Plate XXVI. The chord of the arc of the tunnel, and the height are each nearly 14 feet, the arch being of 4-ring brickwork, in mortar composed of three equal parts of hydraulic lime, sharp sand, and texontle—the latter a species of ferruginous lava. The mortar sets in 36 hours. The invert and side walls consist of artificial blocks, with a backing of volcanic stone in mortar. These blocks are 16 inches by 8 inches by 6 inches, and are made of 1 part of Portland cement to 3 of sand.

Twenty-five shafts were sunk on the line of the tunnel, 1,575 feet apart. The walls are curved on plan, the measurement at corners being 7 feet by 10 feet. The lining is of 18-inch brickwork, and the depths varied from 66 feet to 301 feet. The method of sinking the shafts ultimately adopted is shown by figs. 2 and 3, Plate XXVI. An ordinary single cage, having a car without side-plates, was used, and was run in the usual way on wire guides. The wire guides were attached, at the bottom, to a heavy cast-iron plate, weighing about half a ton. In this plate were bored two holes for the guides. This weight served to keep the guides from swinging, and the cage ran smoothly. The top ends of the guides were passed over pulleys at the top of the head gears, and thence down to the drum of a winch anchored in the position shown on fig. 2. Excavation was carried on all round the cage and lower than the cage, as long as the men could shovel up the dirt into the cars; after this, the middle was cleared out whilst the cage was up, and the spoil shovelled back to the sides to be put afterwards into the car. After excavating two feet or three feet below the weight, the guides were slacked away by the winch, and the weight again allowed to rest on the bottom. The ordinary platform and trap-doors were used above the cage, when down, to keep the workmen from being injured by anything falling. The cage was naturally up while the material was being blasted. Boards were placed against the guides, and neither the guides nor the weights suffered from the blasting. The timbering was in lengths of 16 feet in the usual way, the brickwork being laid on pine frames, 16 inches by 6 inches, which, after the length was lined up, were brick-propped in the ordinary way and sinking was then resumed.

The quantity of water encountered in the shafts varied from 350 gallons to 1,000 gallons per minute. The pumping arrangements are shown on fig. 3. One or two 16-inch double acting Cornish pumps were kept working, each capable of raising 500 gallons per minute to a height of 300 feet. The pumps were placed on strong iron girders, the ends of which rested on oak blocks and ran back 2 feet into the brick-work. They were supported, as usual, on the shafts. The pumps were also slung by a $1\frac{1}{4}$-inch steel wire cable, attached to a 25-ton crab

winch on the surface. This cable was kept just taut to avoid any jar cracking the shaft lining; sinking was carried on to a depth of about 14 feet below the pumps, which had telescopic suction pipes, when the pumps themselves were lowered and connected again in $2\frac{1}{4}$ hours. Quick work was necessary, plunger pumps being in use. In the event of accident and repairs, a diver had to be employed, and he was supplied with electric light and telephone. The water for the most part came down like a rain shower, though occasionally veins and pot-holes of water were cut.

All engines were compound; some of the pumping engines compound surface condensing. Two cages were used, one up and the other down, and at the pit's mouth were two platforms; the lower was used for lowering material and the higher for hoisting spoil. Each platform was provided with turn-tables, two at the back and two in the front of the cages. The pumps were actuated by horizontal-geared engines, the T bobs of the pumps being coupled where two pumps were used. In order to get the pumps into the shafts, the rising mains at the top had to have a set-off to allow them to pass out under the T bobs. The shafts were made bell-mouthed at the bottom simply to allow room for the valve chambers of the pumps. The pipes on the suction pipes were bent in order to allow the cars to pass out of the cages at the back of the turn-tables.

The tunnel was driven largely through sandstone, carrying lime, varying occasionally with soapstone, slickensides, occasionally conglomerates, and, more rarely still, shale. Water existed in large quantities throughout nearly the entire course of the tunnel. In the softer parts the ground always swelled, whilst in the harder parts, if not supported above, it invariably cracked off, and in the cases of soapstone and slickensides slipped off in large pieces.

The tunnel heading measured, inside timber, 6 feet 6 inches in height, 5 feet in breadth at bottom, and 4 feet at top. It had in the middle a water channel 3 feet to $3\frac{1}{2}$ feet deep (fig. 4, Plate XXVI.) for draining off the water. The discharge at the mouth of the tunnel was about 6,000 gallons per minute.

The sections shown in figs. 4 and 5 illustrate the work in the sandstone.

Six holes were drilled, 6 feet 6 inches deep, with mandrils 8 feet long, made of hexagonal drill steel $\frac{7}{8}$ of an inch in diameter. Five cartridges with 1 lb. of Nobel's dynamite were used in each hole, equal to 6 lb. for the face. The cartridges were tied up to laths, the middle one having a quintuple force-cap and fuse to reach 4 feet out of the hole, when the charge was driven in. They were dipped in grease to make them waterproof before being taken into the tunnel. The 8-foot drills were usually put into the holes to keep the charge down. About 210 cubic feet of material were dislodged by each shot on to the timber platform (figs. 4 and 5). In driving three miles of heading in this way, not one man was injured, and the men usually returned from their distance of 50 yards to the face immediately after the shot.

The timbering (figs. 5, 6, 7, 9, 10) had to be promptly done, for although the ground was hard, it began to break away nearly an hour after exposure. It also swelled. The settings were put up at first 6 feet apart (fig. 5), close boarded, and kept within 6 feet of the face. The side trees of the first settings were sawn pine, 6 inches by 7 inches by 6 feet 6 inches, placed on pine blocks, and the head trees, 6 inches by 7 inches by 5 feet. All timbers were cut to their bevel before being sent down, and the brobs driven in the head trees. The polling boards were at once put in, and lightly packed behind with hard lumps of sandstone. Following at about 10 yards' distance, men were employed putting in intermediate timbers, similar to those at the face, but with 8-inch side trees, and extending to the bottom of the drainage channel (fig. 5). Cleats were nailed to them, on which rested the cross-beams for the railway; these also served as stretchers. At the same time, all side trees were stretched under the head trees with 4-inch by 6-inch stretchers, and 12-inch boards laid on each side of the track as gangways. The water channel was sometimes lined, sheet piling being driven outside the rails.

Tipping wagons of 12 cubic feet capacity were used, this size being prescribed by several considerations which need not be detailed here. To provide for the passing of the wagons on the single line of rails, an intermediate setting at 100-feet intervals was left out, leaving a recess on

either side, into which the empty wagon was tilted until the full wagon passed. Fig. 8 shows how the arrangement worked. Wagons 1 and 2 are on the rails on the way to the shaft, while wagon No. 3 is being filled. As soon as the latter passes from the face, wagon No. 4 takes its place, each empty wagon in a recess moving to the next recess nearer the face as the full wagon, No. 3, passes down on its way to the shaft. When recesses were being made, a car was placed on the main track opposite the position of the recess, and the spoil shovelled straight into it, the rule being that, whether this car was full, half-full, or only quarter-full, it must go right out of the shaft as soon as the full car from the face was heard approaching. Thus no time was lost, and spoil never accumulated at the face.

The railway was on the Decauville system—2-foot gauge, with 12-lb. rails and iron sleepers—and was laid in 20-foot lengths. The water channel was excavated with long chisel-pointed bars, and then shovelled out on to the pathway boards on either side of the track, and from there into wagons, the same rules applying to these cars as applied to those taking spoil from the recesses when they were being made—they had to go straight to the shaft. The water channel was never covered in, and the ganger carried a pointed stick with which to probe it as he went along, to see that it was clean.

For ventilation, Root's blowers, No. 1, with 6-inch outlet, were used, each blower being worked by a small engine on the surface, and a 6-inch spiral tube being carried in to within 10 feet of the face, which always gave sufficient air at 700 yards from the shaft. The tubes in the headings were supported by iron hooks driven into the side trees (fig. 4).

This work of driving a heading was undertaken by sub-contractors, who were required to drive in twenty-four hours, a minimum of 8 metres, duly timbered up, with track laid, water channel, &c. The maximum reached was 13·25 metres, the maximum in one month being 222 metres. The sub-contractors were paid a premium for greater speed than the minimum, the amount per metre increasing with each extra metre. The sub-contractor employed two timbermen who put up the timber, and worked 12 hours on and 12 hours off. All the rest of the men below worked only

4-hour shifts, and were not allowed to work two 4-hour shifts in succession, but might work two 4-hour shifts in the 24 hours. No men were allowed to leave the pit until the men of the next shift were there to take up their tools. All changes of shifts were called by the timekeeper at the surface, by having the ventilator stopped 10 seconds. There were 60 men on a shift, including a ganger. The men were divided into shifts of different hours to prevent the foremen always working with the same gang. The engine man on the surface always worked 12-hour shifts, the winding drivers being paid extra to wind in their meal hours. The staff of 60 was thus divided: 2 timbermen, 4 men at the drills, 2 clearing the débris, 22 loading wagons and running them in succession (2 for each wagon), 2 platelayers, 4 men putting in intermediate settings and stretchers, 1 looking after ventilators, 10 working in the water channel, 1 distributing oil and greasing wagons, 1 boy making up explosive laths, 2 hookers on, 2 banksmen, with overseers, foremen, and timekeepers.

Subjoined are details of the cost of driving the heading:—

Number of Heading.	No. 12.	No. 7.	No. 7.
Length of shift	8 hours	4 hours	4 hours
Driven in one week	36 metres	50 metres	70 metres
Sub-contractor	$590·00	$983·92	$1,296·00
Day work	$124·25	$157·00	$222·65
Miners	$42·00	$69·75	$67·75
Dynamite, &c.	$39·10	$51·20	$85·40
Watchmen's wages	$6·30	$6·30	$6·30
Ventilating	$22·60	$22·60	$22·60
Winding	$34·58	$34·58	$34·58
Coal	$178·50	$178·50	$131·00
Timber	$348·00	$425·50	$595·00
Digging ditch	$118·00	$150·00	$210·00
Deepening ditch	$36·00	—	—
Total	$1,703·33	$2,078·85	$2,771·28
Cost per metre	$41·75	$41·57	$39·57

In the first case the miners were paid $1\frac{1}{2}$ shifts each twenty-four hours, and in the other two cases they were paid two 6-hour shifts each.

The process of opening out and lining, when the ground was good, was

carried out in six 21-foot lengths, one ahead of the other, the heading being opened out to the full dimensions at the rate of 26 lineal feet per day. The section given in fig. 7 shows the state of progress at the several lengths. At the toothing end, inverts and side walls are completed, and the ribs set ready for throwing up the arch. The second length has all the bars up, and is lined above water level; the platform erected overhead is to admit of the bars from the lengths further in being removed without injury to the bricklayers below. In the third length, preparations are being made for the bricklayers in the bottom and sides, a wooden trunk being provided for drainage water. In the fourth length, the excavating is completed, but all the timbers are up; the fifth length has three bars up and the nipper sill in, and the sixth length the crown bar up and nipper sill in; while in the latter and beyond, the excavating is proceeding, the material being dropped through holes into the wagons below. The sets of bricklayers worked in shifts day and night, one at invert and side walls, and the other at the arch. Thus a little more than a length was turned in a day, or in a month, excluding Sundays, about 500 feet excavated and lined. As the distance between shafts was 1,575 feet, it was not thought necessary to have break-ups between the shafts.

In heavy ground a full set of timbers had to be used. Iron, however, was adopted in place of wood for the bars, stretchers, and cock-roosts, in view of the less room taken up, and yokes were also used to keep the bars at an equal distance, and keep the stretchers from bending them out of line. The details of these are shown with figs. 9 and 10, and the method of extemporising these various parts is most interesting, and does credit to the contractors' engineers. For bars, three 45-lb. rails were laced and bolted together; 11 of these were used in place of 9 wooden bars, and they were allowed about 3 inches more drop in a 16½-foot span. The bars were always turned the reverse side up, after each length. For bar stretchers, some 3-inch tubular pump rods were cut of different lengths to correspond to the distances between the bars, and a screw 9 inches long turned into one end and a swivel in the other; the heads of both were rectangular, so as to catch well into the sides of the rail bars. The yokes were made of

4-inch × $\frac{5}{8}$-inch iron, and were put on as soon as the bars were up. When once the yokes were on, the stretchers were screwed up tight by means of a strong wrench 2 feet long, which was applied to the middle of the stretcher, where it had been hammered square. The cock-roosts were made of 4-inch pump rods in the same manner as the stretchers, but the head of the screw and swivel respectively were in the form of a fan that fitted diagonally on the side of the rail bars. These were usually about 9 feet long, to reach from the third bar on one side to the ninth on the other, at the point where two cock-roosts intersected. A cast-iron saddle (fig. 10) was placed above them, fitting over both, on which was placed a 3-inch stretcher reaching up to the crown bar. A strong chain was then thrown over the crown bar and under the point of intersection of the cock-roosts. This was hooked tolerably tight, and then the stretcher was screwed up quite tight. The number of cock-roosts put in was, of course, regulated by the weight of the ground.

The result of using iron was, that it formed a very strong well-braced arch. Using 9 bars, averaging in diameter from 12 inches to 14 inches, lengths could be taken out and squared up to only $13\frac{1}{2}$ feet, whereas with the ironwork, lengths of $16\frac{1}{2}$ feet were taken out with ease. Thus a length of 100 feet was worked in one month in one face. Wooden props were used, as iron ones proved too slippery, and it was, of course, impossible to drive nails in them. It follows, that since the iron bars, &c., occupied less room, the area to be excavated was less; fewer men, also, were needed to handle the iron bars, as they were lighter and did not increase in weight, like timber, when wet. The bars, too, were small, and could be passed between the props, were easily drawn, much cheaper, as they can be used for an indefinite number of times, and long lengths could be taken out with greater ease.

The work is now (March 1895) practically completed. It is the longest tunnel completely lined with brick which has yet been constructed, and its magnitude is to some extent indicated by the extent of the plant it was found necessary to use to construct it. 108 engines were employed in pumping, winding, ventilating, sawing, mortar making and brick

making; 5 locomotives were used to haul material. The materials used in the construction of the tunnel were 22,000,000 bricks, these being all made on the works at the rate of 30,000 daily; 1,000,000 artificial stone blocks, made at the rate of 1,000 daily; 706,000 cubic feet of volcanic stone; 880,000 cubic feet texontle and lime mortar; 441,700 cubic feet of lumber. 20,000 tons of coal were burned in the engines and forges, and 1,120,000 cubic feet of oak wood were consumed in lime burning.

The magnificent progress made has been largely due to the splendid organisation—one operation seldom, if ever, clashed with another—and to the working at different jobs simultaneously in the comparatively small heading. The division of the work into very small shifts is also regarded by those associated with the undertaking as a distinct success, as the men engaged in very wet places could work with the greatest activity the whole time of the shift. The arrangement of details was clearly contributory in a marked degree to the expeditious way in which the work has been carried out.

THE OSAKAYAMA TUNNEL, JAPAN.

This tunnel is situated on that portion of the Imperial Government Railways of Japan which has been extended from Kioto to Otzu, a distance of about 10 miles. The line was designed, surveyed, and laid out by Mr. T. R. Shervinton, M.Inst.C.E., the Principal Engineer at the time the works were in progress. The line includes $5\frac{1}{2}$ miles of gradients of 1 in 40.

The Osakayama Tunnel is 727 yards in length, the width at the springing of the arch is 14 feet, and the height from rail level to the soffit of the arch is 14 feet; the gauge of the railway is 3 feet 6 inches. The centre of the line was carried over the summit of the hill, and projected on to hills facing the entrances to the tunnel. From these points, a plumb-bob at each entrance and a mark at some distance from it were lined in, the mark being so placed that both it and the plumb-bob were always visible as the headings progressed, being put at an incline of 1 in 40 to correspond with the gradient of the tunnel.

PLATE XXVI.

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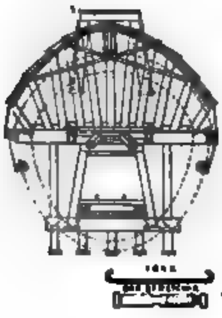


FIG. 9.

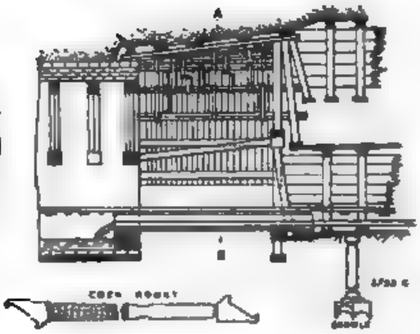


FIG. 10.

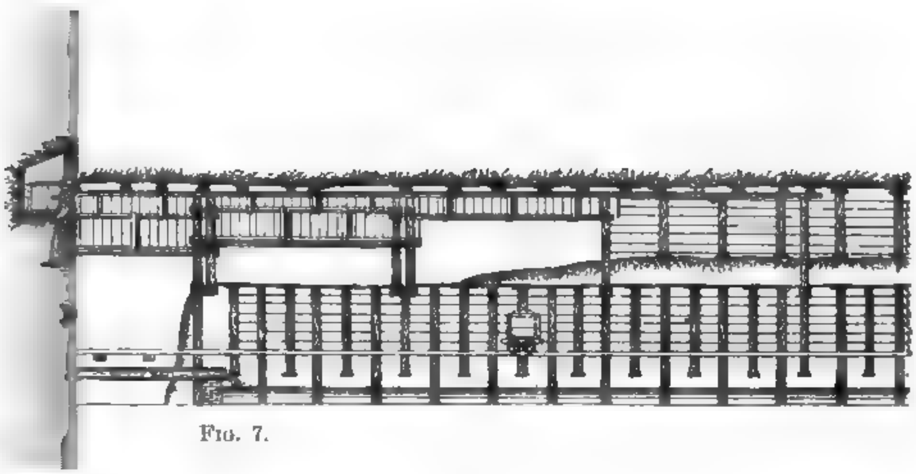


FIG. 7.

FIG. 8

[Between pages 440 and 441.

No machinery was used. Two of Jordan's rock-drills were provided, and the workmen taught to use them; but, the rock being soft at first and much broken, they preferred working by hand. The whole of the excavation was, therefore, done by chisel and pick, with occasional hand drilling for blasting purposes. The inclination of the line through the tunnel was 1 in 40, the direction being from west to east. The tunnel was worked at each end by a heading at the level of the springing. No shafts were used, as the shortest would have been 200 feet long. The headings were 6 feet 5 inches.

The eastern heading was commenced on October 1, 1878. In this heading but little water was met with, and that little passed off down the incline without difficulty. The western heading was worked day and night continuously. Less timber was required for it, owing to the rock being harder; this rock, however, was intersected by small clay veins, which rendered it liable to fall in masses of dangerous size. Owing to the falling gradient, the water had to be pumped up, but the quantity was not large. The pumps were made from large bamboos, with a cross-handled plunger, and were worked in short lifts.

Following the headings, the excavation was carried out to the full dimensions. The arching, of either two rings or four rings of brick, was turned throughout, except in a short length of treacherous ground, where six rings were used. The arching was underpinned by side walls 1 foot 6 inches thick on the entire north side. On the southern side for nearly the whole length, the side walls consisted of 4 lineal feet of wall, 1 foot 6 inches thick, and 6 lineal feet of wall, 9 inches thick alternately. Old 15 feet centres, with a rise of 5 feet 6 inches, which had been used for bridges on the line below were employed; two longitudinal beams and a transverse beam being added with the wedges, to make up the difference between 5 feet 6 inches and 7 feet 9 inches, the inside radius of the arch, when there were only two rings of brick. A smaller centre on the same principle was used, when four rings were necessary, the radius being 7 feet. By this method the top part of the centres was small enough,

when lowered, to be passed ahead easily, and was found handy as well as cheap.

Ventilation was kept up by fans working at the end of long air-tubes, within closed doors, at stated points, the air being passed through the drainage water for the purpose of cooling it.

No European supervision was employed, with the exception of that of the District Engineer. The immediate charge of the work was in the hands of Mr. Kunisawa Yoshinaga, a Japanese engineer cadet educated on the railway works below.

Only one accident occurred, due to the fall of some loose rock whilst shifting struts in a careless manner, whereby three labourers and a miner were killed. This fall delayed the completion of the east heading, but not seriously.

The headings met, the lines and levels being correct, on September 10, 1879. The brickwork was completed on June 1, 1880. The first engine passed through the tunnel on June 26, 1880, and the line was opened for traffic by the Mikado on July 14 of the same year.

The cost of the tunnel is shown by the following statement:—

	Paper Yen
Labour for excavation	85,733
Bricklayers	11,824
Masons	909
Carpenters	2,258
Cartage, assistant labourers	33,952
Timber	8,873
Sand	2,014
Cover stones for drain	660
Rubble	1,161
Clay puddle	330
Lime, 2,507 cubic feet	300
Portland cement, 4,100 casks	33,976
Bricks, 2,312,948	20,817
Sundries	3,440
Total	206,247

This, at a rate of exchange of 3*s.* 10*d.* per dollar or yen, less 15 per cent. discount for paper money—that being the then current rate—gives the total cost to be 34,374*l.* 10*s.*

The wages paid were :—

	Yen.	Sen.	Yen.	Sen.
Miners, 6 to 8 hours per diem	0	50	0	80
Carpenters " "	0	40	0	70
Masons " "	0	40	0	50
Labourers (Coolies), 8 hours per diem	0	20	0	40

100 sen = 1 yen

The number of miners employed was :—

	Man-days.
Miners for heading, 4 shifts a day, four men working at the same time	10,880
" enlarging heading, 3 shifts	8,160
" for lower excavation, 3 shifts, four men to each shift	9,000
" excavation to formation, 3 shifts, six men to each	17,380
" " for drain	1,518
" " side walls, six men for every five feet on each side	5,200
" enlarging top for arch	19,360
Total	71,498

The above figures relating to cost and labour have been obtained from details supplied by the Japanese officials, and are based on daily averages, small delays not being included.

THE PANIR TUNNEL

(THROUGH LIMESTONE ROCK).

This tunnel is 3,050 feet long, and is laid for a double line of rails of the Indian State Railway standard gauge of 5 feet 6 inches. The headings met on August 31, 1893.

The Belgian system has been adopted in this work, a top heading having been first driven; this is enlarged for the arch, and is finally carried down to the foundations by underpinning.

In the present instance, the arch is semi-circular and is of 29-foot 6-inch span, the height above rail level being 20 feet 9 inches. The excavation has been through limestone rock. Four-inch Climax power drills were used, which were worked by natives. Two of them were mounted on one stretcher bar, and, using air at 60 lb. pressure, 25 holes 45 inches deep could be driven in five hours. The drill bits were $1\frac{7}{8}$ and $1\frac{1}{4}$ inch in diameter. The explosives used were dynamite and gelignite. The compressing plant

was situated on the north side of the tunnel, and the air was conveyed to the drills on the south heading by an air main of $4\frac{1}{2}$-inch wrought-iron pipe 6,000 feet long, which was laid over the hill. The average rate of progress was 13 feet per day at the two working faces. The best month's work was, however, 455 feet, equivalent to a rate of 15 feet a day. The temperature, both inside and outside the tunnel, was very high, the average being 100° F. at the working faces. Outside it was higher still, 117° F. in the shade being registered on one occasion. This high normal temperature made it necessary to adopt special means for cooling the air-compressors, as the water available had a temperature of 112° F., and was therefore almost useless for the purpose. The cylinders were therefore lagged with old rope and grass, which was kept moist with water at intervals.

The tunnel is on the Mushkaf Bolan Indian State Railway, and commences at the 475th mile of the North Western Railway. It penetrates a high range of limestone hills which divide the Mushkaf from the Bolan Valley, the latter being 200 feet lower than the former. The first train passed through the tunnel in May 1895.

THE KHOJAK TUNNELS.

The Khojak Tunnels are situated on the New Chaman extension of the North-Western State Railway. The tunnels are divided into three sections, known respectively as Khojak, Khojak I., and Khojak II., and the position of the tunnels with reference to the nearest stations are at Shilabugh and $3\frac{1}{4}$ and $6\frac{1}{8}$ miles below that station respectively.

The total length of the Khojak Tunnel is 12,870 feet, of which 1,422 feet is half lined and 11,448 feet three-quarter lined. The total cost, including tools and plant, is 68,53,145 rupees, the cost per foot-run being thus 532 rupees. The driving of the heading occupied $2\frac{1}{2}$ years, the work having been commenced in April 1889 and completed in September 1891. The heading was principally through shales bearing water and layers of soft

mud. It has been found necessary to underpin the half-lined portion of the tunnel, so that the tunnel will shortly be three-quarters lined throughout.

The tunnel is constructed for a double set of rails of the standard 5-foot 6-inch Indian State Railway gauge.

Khojak tunnels Nos. I. and II. are much smaller as regards length, being only 750 feet and 800 feet respectively. The cost of No. I. was 2,24,028 rupees, and of No. II. 2,57,291 rupees. The driving of the headings occupied 4·13 months and 5·33 months respectively, both being completed in 1890. The material closely resembled that of the Khojah Tunnel referred to (*ante*), consisting mainly of soft and hard shales with beds of mud at intervals. No. I. tunnel was on the cut-and-cover system on 902-foot radius. No. II. tunnel has a 819-foot radius. The cost per foot-run is 296 rupees and 322 rupees respectively.

MANCHESTER AND SHEFFIELD RAILWAY (EXTENSION TO LONDON).

The accompanying figures show sections of the tunnels now in course of construction on the extension of this railway to London. Only where the

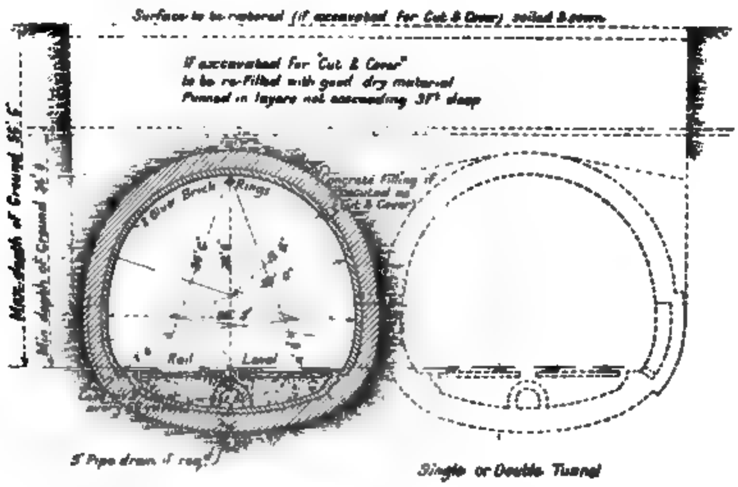


FIG. 1.

depth exceeds 40 feet will tunnelling be resorted to, in which case the section shown on fig. 1 will be resorted to. The normal section for cut-

and-cover will be that shown by fig. 2. In both cases the height above rail level is from 17 feet to 20 feet, and the width 26 feet 3 inches. Fig. 3 is a standard gauge diagram, and shows in detail the dimensions of the bridges, tunnels, platforms, &c., to be built on the line.

The seven lines of this railway which will enter the London terminus about to be built in the Marylebone Road, will pass under Lord's Cricket Ground through three tunnels, two of 26 feet 3 inches in width, and one of 43 feet, the latter being for three lines of rails. The total width of working is 124 feet, and the work will be carried out as quickly as possible on the cut-and-cover system.

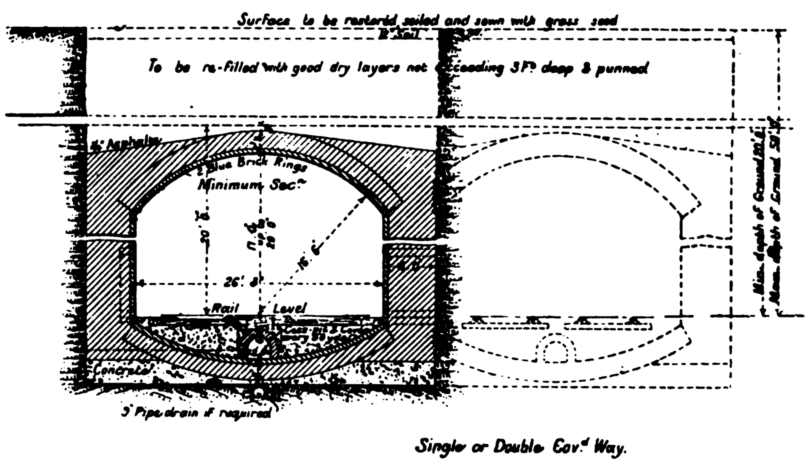


FIG. 2.

Ninety-two miles of new railway have to be constructed, and these have been divided into Northern and Southern sections; and of the latter, which extends to Rugby, Sir Douglas Fox and Mr. Francis Fox are the engineers. The only tunnel of importance on the Southern section is one 2,860 yards long, commencing 27 miles from Quainton Road Station. It is mostly through clay, and for the most part the formation level is 100 feet below surface, while at the northern end it is 120 feet below. The lining of this tunnel at Catesby section is of seven-ring work, the two inner rings being of blue brick. The height from rail level, according to the maximum section, is to be 20 feet 6 inches, the extreme width being 27 feet. The refuges are 7 feet high, and 3 feet 6 inches by 1 foot 6 inches

deep, and are placed on each side of the line at intervals of 60 feet. Imposing portals with wing walls 10 feet 6 inches at bottom and 2 feet 3 inches at top, and curved to a radius of 30 feet, are to be constructed. The slope above the portal is 3 to 1 and 4 to 1.

Beyond Rugby the line enters upon the Northern section, which joins

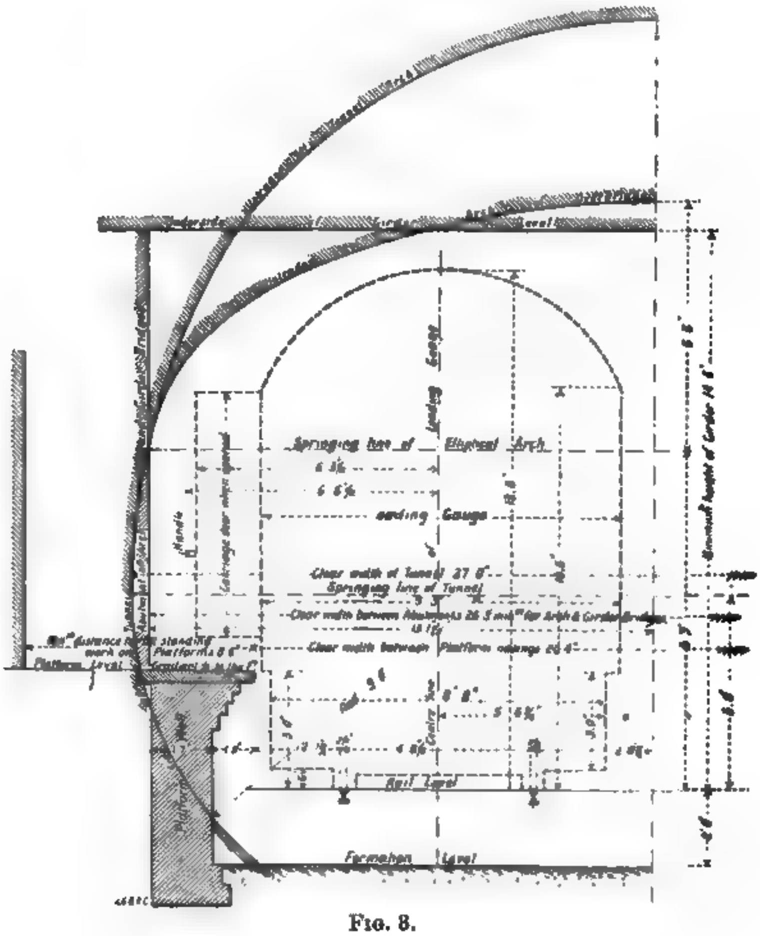


Fig. 8.

the existing Manchester, Sheffield, and Lincolnshire Railway system at Annesley Junction. The first tunnel on this northern section is one 88 yards long near East Leake. The material through which this has to be driven is lias, shale, &c., and lining of five-ring brickwork will be required throughout. The sections to be adopted will give a height above rail level of 20 feet 6 inches. Refuges are placed at 66 feet intervals, alternately on

both sides of the railway. These are 3 feet 6 inhces and 1 foot 6 inches by 7 feet high.

The next tunnel on this section is at Mansfield Road, Nottingham. It is 1,200 yards long, opening out for a short distance at the bottom of Sherwood Rise, and proceeding thence by the Sherwood Rise Tunnel, 662 yards in length, towards Basford. All the tunnelling in Nottingham will be of the New Red or Bunter sandstone, which is not expected to require lining except at the crown, which is being lined with four-ring brickwork. The width is 27 feet, and the height above rail level 20 feet, the radius being 16 feet 7½ inches. The same section will be adopted in the three tunnels. At intervals of a quarter of a mile, manholes will be provided 10 feet deep from the tunnel walls, 10 feet wide, and 9 feet 6 inches high; the arching of these being of four-ring brickwork on a radius 6 feet 6¼ inches. These are in addition to the ordinary refuges.

CHAPTER XXXII.

SUB-AQUEOUS TUNNELLING THROUGH CLAY, GRAVEL, ETC.

THE VYRNWY AQUEDUCT.—TUNNEL UNDER THE MERSEY.

SOME important tunnelling works have been constructed in connection with this aqueduct, which supplies the City of Liverpool with water—the source of supply being the Vyrnwy Valley, which has been converted into a lake by the construction of an immense dam. The aqueduct is 68 miles long to the Prescot reservoir, or 77 miles to the Liverpool Town Hall. It consists almost entirely of piping, there being only three tunnels throughout the entire work.

The first and longest is the Hirnant Tunnel, 2 miles 3 furlongs in length. It is through rock, chiefly Silurian, and was driven from both ends. Compressed air drills were used, and the speed at each face was about 10 yards per week, with two shifts of eight men, working 10 hours per diem. It is lined, where necessary, with brickwork, varying from two-ring to four-ring. The next tunnel is the Cynynion Tunnel, at mile 16. It is 7 furlongs long; but the aqueduct only comes out of tunnel to pass in syphon across a valley, entering the Llanforda Tunnel, which is 1 mile long. The total length of tunnel is therefore 4 miles 2 furlongs. The tunnels are circular in section, of 7 feet diameter, and the linings, where used, consist of two- to four-ring brickwork as above mentioned. The most difficult part of the work, however, was in connection with the driving of the aqueduct tunnel under the Mersey, near Fidler's Ferry, about 14 miles from the Liverpool landing stage.

The original plans were prepared for presentation to Parliament in 1879 by Mr. T. Hawksley and Mr. G. F. Deacon. In these, the place of crossing the river was chosen with a view to the pipes being laid in the loose material composing the river bed, and, had a tunnel of any kind been then contemplated, it is probable that this site would not have been chosen. The comparatively simple arrangement of laying the pipes in the river bed was opposed by some of the riparian authorities of the Mersey above Runcorn, who alleged that the river would probably be deepened for navigation purposes, and, in order to prevent further opposition in the passage of the Bill through Parliament, it was thought expedient to accept a clause, which referred the mode of crossing the Mersey to the Board of Trade. The year 1881 was thus lost, and in the years immediately succeeding efforts were made—which were, however, not successful until 1885—to pass the Ship Canal Bill. It was believed that the existence of a ship canal would remove the last chance of the Mersey being deepened above Runcorn, to such an extent as to interfere with the original intention in respect to the construction of the aqueduct. Borings were made by the Liverpool Corporation in 1886, which showed the ground to be suitable for laying the pipes in the bed of the river—more suitable, in fact, than it subsequently proved to be for tunnelling. The decision of the Board of Trade was communicated in November 1887, and was to the effect that the aqueduct should not only be laid a few feet deeper than the bed of the river, but that the pipes should be laid so that the upper portion of any projecting material connected with them should not be less than 17 feet below Ordnance datum, throughout the whole breadth of the channel of the river. The Ordnance datum and low-water channel are, at this point, practically at the same level, so that the highest part of the work required to be 17 feet below low-water channel, and the width of the river is 800 feet. Mr. Deacon, who was then the sole engineer for the works, therefore advised that a tunnel should be bored. Any alternative course, such as altering the position, would have involved delay, as a new Act of Parliament would have to be obtained; and additional expense would have been incurred by the purchase of the requisite land

and easements. It was, therefore, decided to construct a tunnel through the formation, which was believed to be the most suitable for that purpose.

The necessary plans and specifications were accordingly prepared; and on October 30, 1888, a contract was entered into, and the work was shortly afterwards commenced by the contractors. The sinking of the shafts on either side of the river formed the initial portion of the work. The Cheshire shaft was sunk to a depth of 85 feet, and the driving of the tunnel began at that depth and extended under the river for a distance of 57 feet 6 inches from the shaft. The Lancashire shaft was sunk to a depth of 96 feet. The Cheshire shaft was sunk by putting together the cylinders forming the lining of the shaft and weighting them, so that, when the material was excavated, they steadily sank. The driving of the tunnel was carried on in the usual manner for a considerable length, the material being timbered temporarily, until the segments forming the tunnel were constructed. It was discovered subsequently, however, that the ground through which the tunnel was being driven was bad, and consisted of mixed strata. An air-tight deck was formed in the shaft, with a lock, and the work carried on for some time under air pressure. Difficulties and disagreements arose, with the result that the contractors stopped work.

Fresh tenders were then invited for the completion of the work, and that of Messrs. Cochrane & Sons, of Westminster, was accepted. The firm, however, having made further investigations, came to the conclusion that it would be simpler to drive the tunnel through the loose water-bearing strata at a higher level, and they eventually declined to sign a tender for the completion of the work on the existing lines, on the grounds, stated in the contract, that, 'owing to the extent to which the natural strata, near the bottom of the Lancashire shaft already completed, and near the part of the tunnel at the Cheshire end already constructed, had been disturbed, by the mode of working previously adopted, great difficulty and risk would attend the completion of the works at the same level, or even at a somewhat greater average depth.' While believing that it was possible to drive the tunnel at either level, Mr. Deacon expressed the opinion that the risk to life was now probably less at the higher, than at the lower level,

and it was, therefore, decided to allow Messrs. Cochrane & Co. to proceed with the work at this higher level. The difference between the two levels was 51 feet 3 inches, the old tunnel having been 104 feet below the surface, and the new tunnel being 52 feet 9 inches.

Air-compressing and Lighting Machinery.—Two new air-compressors were provided; two new 40-horse-power pumps; two sets of electric lighting plant; and a Tangye pump for working the hydraulic jacks in the shield, and in connection with it an accumulator. One of the compressors was by Messrs. Owen & Co., London, and the other by Messrs. Walker & Sons, Wigan. The air was passed into a reservoir for cooling and storage. One of the electric light installations was by the Brush Company, and was driven by a Robey portable engine and boiler; and the other was driven by an engine made by the Phœnix Foundry Company, Chester, steam being supplied by two of Messrs. Davey, Paxman & Co.'s boilers, which also worked the compressors. These two boilers are interchangeable. The provision of electric light plant was most effective, as it afforded good light to the men underground, and at the same time kept the air sweet. There were three wires laid along the tunnel, one for the lead, one for the return, and a spare wire; and the wires and lamps were tied up to the bolts on the flanges. There were, in addition, several portable lamps for working at the face. The plant altogether was found suitable and efficient.

Shafts.—It was decided, when operations recommenced, to make a new shaft on the Cheshire side, 20 feet to the east of the old one, while the shaft on the Lancashire side was to be enlarged. (For illustrations of these shafts, see figs. 1 to 3, Plate XXVII.) At the Lancashire shaft, the tunnel is 52 feet 9 inches deep, and at the Cheshire shaft 46 feet 6 inches deep, below ground level. The shafts are 10 feet 9 inches in external diameter, the Lancashire one being widened out to 13 feet 9 inches, and the Cheshire one to 15 feet in diameter. This work of enlarging the diameter was first undertaken. The old shaft was constructed of iron rings, in one piece 4 feet deep, the metal varying in thickness from 1 inch to $1\frac{1}{16}$ inches, according to the depth. At a depth 36 feet below the surface, an old cylinder

was cut and replaced by segments of cast iron, 3 feet by 18 inches, bolted together. The first of these was bevelled, so as to make up for the increase in the diameter of the shaft, from 10 feet 9 inches to 13 feet 9 inches. The metal of the segments was $1\frac{3}{4}$ inches thick, and the flanges were six inches deep, jointed by 1-inch bolts. The remainder of the old cylinders were taken out in rings, the area of each of the new segments being drilled out one at a time, and the new segments put in position. The work had to be done under air pressure, as the material outside the shaft was wet sand, and the space around the outside lip of the shaft was kept filled with clay to prevent the escape of air. The pressure of air required was 20 lb. to the square inch. The bottom of the shaft was covered with a curved deck plate, with a key-ring to connect to the segment of the shaft.

The new Cheshire shaft (fig. 1, Plate XXVII.) was sunk in the usual way. An automatic grab dredger was used for excavating. The iron skin of the shaft was loaded, to produce a weight of about 2 tons to the foot of cutting edge, which was made about one inch greater in diameter than the external measurement of the shaft, to reduce surface friction. It was sunk without difficulty to the required depth, and the bottom covered with about 6 feet of concrete tipped from trap boxes, lowered through the water, lying in the bottom. The water was then pumped out and the weights removed. The cast-iron invert casing was then fixed. Blank flange openings were left on the side of each shaft for the driving of the tunnel. This work was done under compressed air.

The tunnel under the river is 805 feet long, 10 feet in diameter outside, and 9 feet inside the flanges (fig. 4). It is built of rings, 1 foot 6 inches long, of segmental plates, with inside flanges. There are in the circumference 10 segments, 3 feet by 1 foot 6 inches, each weighing about 4 cwt., and the key piece on each ring is 10 inches by 1 foot 6 inches, weighing about 1 cwt. The thickness of the segments is $1\frac{1}{16}$ inches, and the space between the flanges is left tapered, in order to retain the Portland cement, with which these are caulked. The junction between the tunnel and the shafts is clearly shown by the diagram (fig. 5, Plate XXVII.). Details need not therefore be entered into.

When the full supply is being drawn from Lake Vyrnwy there will be three pipes through the tunnel. Provision has been made in this section for a greater fall per mile than elsewhere, so that the steel pipes through the tunnel might be reduced in diameter without loss of discharge in power. The steel tube enters through eye-holes on the Cheshire and Lancashire shafts with a 10-feet sweep, and hangs vertically down the shafts, supported on trunnions on cast-iron girders. The curve to the Lancashire shaft is of cast-iron pipes with deep sockets, and is connected together by links over trunnions, as shown on fig. 3. The curve to the Cheshire shaft is of steel pipes with a triple-ported horizontal valve. This curved pipe is formed of bevel steel plates, quadruple-riveted. Cast-iron girders are placed in the shaft, which are shown on figs. 1 and 2. The main girder spanning the shaft is of ⊥ section, 6 inches wide at top, 11 inches at bottom, and 18 inches deep. On the bottom flange there rest two cross girders, with Plummer blocks, and on the pipe is a trunnion which engages in the block. Another 10-foot radius bend at the bottom of the shaft, in both cases of steel, connects the vertical and horizontal portions of the steel tube. The horizontal part is carried through the tunnel on the up stream side and rests on greenheart bearers, as shown on fig. 4. The centre, however, is left free, the cradle being made with two timbers wedge-shaped in section. The cradles again lie upon greenheart timbers, 6 inches thick, placed at 6-feet intervals across the tunnel. This is to admit of repairs being executed without stopping the supply. Between the steel tube and the bye-pass there is a chequered plate footway, with side railing. There are iron ladders and platforms on both shafts (figs. 1 and 3), while at the top of each shaft a ventilating tower is erected, through the doors in which, access to the tunnel is obtained.

Pumping Machinery.—There is a fall from the Cheshire to the Lancashire shaft of 6 feet 3 inches, and in the latter shaft a sump is constructed, as shown in fig. 3, into which any water in the tunnel will drain. To raise it, in order to pass it into the river, an hydraulic pump, worked by pressure from the main, is placed in a cast-iron engine chamber, built under ground level on the Lancashire side, entered from the shaft. This chamber is shown on fig. 2.

This pumping machinery was designed by Mr. Deacon, and constructed by Messrs. Easton & Anderson, Limited. Figs. 6 and 7, Plate XXVIII., show the general arrangements of the machinery. The pump is worked by an hydraulic engine, and a connecting rod from this engine actuates the cast-iron rocking beam previously referred to. This beam, as will be seen on reference to the diagrams, is carried on pedestals at the top of the tunnel shaft. Each end of the rocking beam has attached to it the cast-iron pump rods, working on separate rising mains attached to gun-metal barrels on either side of the shaft, 20 feet above the bottom of the sump (fig. 6). The clack and bucket valves are made of gun metal with delta metal spindles. They are of the double-beat pattern, and can be removed without lowering the water. On fig. 7 there is shown a copper float in the sump. By means of this float the valve of the hydraulic engine is actuated. The float, rising with the influx of water into the sump, opens the connection between the main aqueduct and the valve, and sets the engine in motion. The pressure is again shut down when the water is pumped down, until the sump is nearly emptied.

The hydraulic engine actuating the pumps for keeping the tunnel clear is worked by the pressure in the main aqueduct pipe. It has a cylinder of gun metal $8\frac{1}{2}$ inches in diameter, and a gun-metal piston with a stroke of 13 inches. The piston rod is of delta metal. The slide valve is of the D type, and is actuated by a small auxiliary cylinder $3\frac{1}{2}$ inches in diameter, the piston stroke being 6 inches. It acts like a cataract cylinder, so that the speed of the main engine is easily regulated. The valve of the smaller engine is worked by links from the crosshead of the larger engine. The valve for regulating the supply of water from the main aqueduct for operating the hydraulic engine acts automatically. An equilibrium valve is fixed on the combined exhaust pipe from the cylinder, and is actuated through the agency of a copper float in the sump, as above stated, which rises and falls according to the level of the water in the sump, so that, when there is an influx, the valve is opened and the hydraulic engine started. A connecting rod from the crosshead to the engine actuates the cast-iron rocking beam, to which are attached the pump rods as already described.

The Shield and Air Lock.—It has already been mentioned, that in constructing the shafts an opening was left for the passage of the shield, and which was temporarily closed with cast-iron plates. When the shaft was completely sunk, these plates were removed, and the shield for driving the tunnel was put in position. The vertical air lock (figs. 10 and 11, Plate XXVIII.) fitted for the widening of the shaft also served for subsequent operations. The lock was about 7 feet high, and 2 feet 6 inches in diameter. It was fitted in a wrought-iron deck, specially constructed so as to be attached to the under side of one of the horizontal flanges in the shaft. The shield in its original form consisted of a skin constructed of two $\frac{3}{8}$-inch steel plates made to break bond. All the rivets on the outside were countersunk to give a smooth surface. The length of the shield was 11 feet 7 inches, and the outside diameter 10 feet 3 inches, giving an inside diameter of 10 feet $1\frac{1}{2}$ inches. The distance between the diaphragm and the cutting edge was 3 feet. The diaphragm was made up of sections, and extended across the face, with a small door at the bottom. Behind the diaphragm, which was specially stiffened round the outside by angles, were nine hydraulic rams. These were 7 inches in diameter with a stroke of 2 feet, and were strapped in cast-iron cradles each having at either end a flange, so that each butted against and was bolted to the adjoining cradle, thus forming a ring immediately inside the skin of the shield (fig. 8, Plate XXVII.). The cradles were tightened up to the skin with wedges. The cylinder of the ram was fixed to the cradle by straps secured by studs, as shown on the section (fig. 8). The cylinders abutted against the stiffener attached to the diaphragm, outside which there were gussets of angle-iron and web plates to take up the thrust. The rams worked against the flanges of the finished edge of the tunnel when it got well started.

It was intended at the start to loosen the materials in front of the diaphragm by means of water jets, ten holes being provided (fig. 9, Plate XXVIII.), but, owing to the strata containing some clay and gravel and varying very considerably, this method was not found satisfactory, and the excavation proceeded through a small door, radial in form, in the bottom of the diaphragm. This small door, which was 2 feet 6 inches by 1 foot 9

inches, was made of a single plate, so that it could easily be bolted on. The operations were carried on for some time through this opening. When, notwithstanding the air pressure, the stratum became insecure and showed signs of running, it was checked by the men blocking the opening temporarily. On one occasion this method was not effective, and some water and sand found its way into the tunnel. Sometimes the stratum stood well, and it was possible for the men to get in front of the diaphragm to excavate, and then good progress was made. In that case the middle circular plate and the radial one above were taken off, so as to afford better facility for egress. While the three openings were being used, the precaution was taken to attach upright timbers to the diaphragm on either side, and cross planks were fixed to these uprights by pins and cottars, and as few planks as possible were taken off at one time. Operations were then continued for 20 weeks, until the beginning of September 1891, and during that time 48 yards had been driven.

Meanwhile progress had been made with the horizontal air lock in the shaft, as it was found very inconvenient to have the lifting of the material checked in passing through the upper air lock. The horizontal lock, of which an illustration is given, was constructed of brickwork, which was continuous at the sides, and, to lessen the cost of construction, the roofing of the locks was planked over instead of being of brick arching. The walls were 5 feet 6 inches in thickness, leaving a span 3 feet 6 inches wide in the middle for standing room. The doors were of cast iron, and made tight by continuous india-rubber rings on the face. There was on the pressure side of the cast-iron frames for the doors, a 3-inch groove cut through the brickwork to the skin of the tunnel, into which space hydraulic lime grout was injected to insure air-tightness. A 9-inch main air pipe passed through the brickwork into the tunnel. For charging the lock from the outside, there was a pipe from the tunnel to the outside, where it was regulated by a cock, and thence into the lock. For discharging the pressure in the lock, another pipe passed from the lock to the outside, where a cock was fitted. For working the lock from the inside, there was a pipe from the tunnel and another from the outside.

There was another pipe 9 inches in diameter right through the air lock, for the purpose of passing rails for use in the tunnel. It had a valve at each end. This pipe also served another purpose. A branch was fitted to it on the tunnel side, to which there was attached a flexible hose carried to the working face. Through this hose, water was forced by the air pressure in the tunnel. This water passed into the bottom of the shaft, and was raised to the top level by a force pump. Another pipe served to indicate by gauge, on the outside, the pressure in the tunnel. Later on in the operations, it was found desirable to construct a safety lock of large size on the tunnel side of the ordinary lock. In this safety lock there was room for all the men, and as the door was kept open it was always ready to receive them in case of emergency.

After the horizontal air lock was put into operation, the men declined to work with the three openings in the diaphragm, as before, for, notwithstanding the safety lock, they believed the danger to be increased, owing to the absence of any direct means of escape into and partly up the shaft. Only the bottom opening in the diaphragm was, therefore, left open, and, as a further precaution, planks were stretched across the tunnel a few feet behind the diaphragm, and built up to such a level that the top of this barricade was slightly higher than the top of the opening in the diaphragm, thus forming a water trap. As can readily be conceived, progress was slow when working through the bottom door, and the 'spoil' continued falling from above as the men excavated, so that, instead of excavating 3 cubic yards to the lineal foot, they were taking out 6, 7, and 8 yards. To prevent the stuff above the line of tunnel coming in, runners made of channel iron were driven through grooves cut in the diaphragm near the centre line. These runners were about 6 feet long, and were driven 3 feet beyond the cutting edge into the solid ground. Six of these runners were used. They were placed 12 inches apart, each being 5 inches wide. This temporary roofing in advance prevented any extensive fall of the strata above.

The work was slowly going on in this way, when it was noticed that the shield had commenced to move out of line, tending to the left, notwith-

standing that the rams to the left side of the shield alone were at work. An examination showed that the cutting edge had buckled in to the extent of about 12 inches for a length of 6 feet outside the shield. The whole work was brought to a standstill, and at great risk the workmen went in front of the diaphragm and boarded up the face of the shield at the cutting edge.

Stoppage of the Work.—About this time the contractors declined to proceed, and serious doubts were raised as to the possibility of completing the undertaking. Since its commencement by the former contractor, the work had occupied more than forty-one months, and only the two shafts and 182 feet of the tunnel had been finished. There had been repeated accidents and hairbreadth escapes, two contractors had given it up, and it was not unnatural that, notwithstanding Mr. Deacon's assurance that he could finish the work, and a repetition of his former offer to do so without the intervention of a contractor, the Liverpool people should desire to obtain the opinion of an engineer unconnected with the undertaking, as to whether the completion of the tunnel, on the site chosen, was practicable. With Mr. Deacon's concurrence, therefore, Sir Benjamin Baker was called in to give his opinion on this point, and he entirely agreed with Mr. Deacon's view that the work was practicable.

Sir Benjamin, in his report dated October 3, 1891, stated that he was familiar with the details of the execution of nearly every work of similar class which had been carried out in America; and that although there are altogether several miles of waterworks tunnels under lakes and rivers on that continent, in no instance was the soil to be tunnelled through so varying in its character as that found at the Mersey crossing. Past experience, therefore, afforded little help. He had no doubt in his mind that the delay and disappointment were not due to any inherent impracticability in the undertaking, but were consequent upon the several contractors underrating the difficulties and making an insufficient provision in the way of plant to surmount them. Thus, the first contractor knew from the borings that he would have to deal with clay and occasionally gravel and sand, but he laid out his works for clay only; whilst the second

contractor provided a shield, which might possibly have worked if sand or fine gravel alone had to be dealt with, but was not adapted for the mixture of materials known to exist. (Here it may be mentioned that the shield, being a temporary appliance used by the contractors, the engineer had nothing to do with its design, and could only make suggestions.) Sir Benjamin pointed out that the contractors were attempting something which had never been done before, and that it is not given to one man in a thousand to be a successful inventor. The shield ought to have been capable of dealing with gravel, running sand, and clay in any order of stratification, and to control the escape of compressed air. He had no doubt such a shield could be designed to work successfully, and that the tunnel could then be completed at a reasonable rate of speed.

Under these circumstances, the Corporation decided that the work should be continued by Mr. Deacon, and accepted his proposal to do it without the intervention of a contractor. The sequel will show that he had not been too sanguine as to the result. More than a month was lost before the work could be resumed. It was then, so far as the driving of the tunnel was concerned, speedily finished in less than four and a half months.

The damaged part of the cutting edge was, on the resumption of operations, cut out by drills, new plates being bolted on, whilst at the same time the number of stiffeners on the cutting edge was doubled round the whole circumference. In addition there were attached, at equal distances from each other, eighteen steel points projecting six inches in front of the cutting edge. This change was suggested by the efficiency of claws on the buckets of a ladder dredger or the claws on a grab bucket. The teeth on the cutting edge were set to be one inch greater diameter than the cutting edge, thus forming grooves round the shield and so reducing friction. The diaphragm was slightly altered. Formerly the opening parts were a circular part in the centre with radial parts at top and bottom, the apex in each case abutting on the circular part. The top part was left as it had originally been, three inches below the centre line, while the bottom part was made up of three horizontal strips, extending from side to side of the shield, and so placed that any or all could be

removed according to the nature of the ground being excavated. The space for driving the runners for temporarily supporting the ground above, in front of the diaphragm, was still left. At the same time the number of rams was increased from nine to ten, so that their thrust might be against the longitudinal joints of the segments forming the completed skin of the tunnel, and thus prevent breakage of cross flanges, which had occasionally occurred when working with the nine rams. To equalise the thrust on the ten rams of the diaphragm, which had only been made originally for nine rams, a circular cast-iron girder was made and fitted between the rams and the inside of the diaphragm. In substitution for the boards—which, as already stated, had been placed behind the shield to form, in case of necessity, a water trap—a more permanent wrought-iron receiver was fixed, with a lid so constructed as to slide over and close the space between this stop and the diaphragm. This arrangement, as well as that of the teeth on the cutting edge, was due to a suggestion of Sir Benjamin Baker.

Resumption of Operations.—Work was started under the new conditions on November 12, 1891. Up to this time 182 feet out of 800 feet had been driven by Messrs. Cochrane. On the first day the bottom horizontal strip only was removed from the diaphragm for the excavation of material, with the receiver at its full height, but, as the men soon gained confidence, the other strips were removed on the following day and the work proceeded rapidly. Within a week, the men were again out in front of the diaphragm working as they had done when the air lock was half-way up the shaft. As soon as the system was found to be successful, an arrangement was made with the men, whereby there was distributed among them a bonus for every foot extra driven during any week beyond 18 feet per week; and it may be noted here, that in one subsequent week they did 57 feet. Work proceeded satisfactorily, 120 feet being driven within a month of the resumption of work. On February 11, 1892, an inrush took place which filled the receiver, but, the lid having been closed, it did not overflow, so that the arrangement proved effective. After operations had been suspended for three or four hours, the pressure in the tunnel having slightly increased, the lid was drawn back, when it was found that the

sand which had run in had dried. Excavating operations were then resumed.

It was shortly afterwards noticed that the end of a tree lying parallel with the tunnel was hard up against the diaphragm on the top left quarter. This tree had to be cut away eighteen inches at a time, as the shield advanced. This cutting was done through the hand hole 6 inches in diameter originally made for observation, and situated 2 feet 6 inches above the centre of the diaphragm. This, as may naturally be inferred, caused great delay, the tree being 14 feet long, whilst the diameter was 12 inches. It was in a fair state of preservation in the centre. Operations were then continued until the tunnel was immediately beneath the deep channel, when, on the morning of February 18, 1892, the ground began to drop from the top cutting edge of the shield. The men then came in from the front of the diaphragm and worked in the receiver; as the shield did not advance steadily, the covering of the hand hole was taken off for observation, when it was found that a log of wood was pressing against the diaphragm. While this examination was taking place, the pressure in the tunnel was reduced about 4 lb. The hand hole covering was put on again, and the pressure was beginning to accumulate, when the wetness always noticeable at the bottom of the fall increased, and soon became a small stream, which rapidly increased. The men made a desperate effort to slide the lid back, but became scared, left it open, and rushed for the safety lock. The water and sand rushed in with such velocity that it struck the roof of the tunnel near the rams. The sand filled the tunnel near the diaphragm up to about 3 feet from the top, but sloped very gradually almost to the back end of the tunnel. Everybody escaped into the safety lock. As the sand choked the suction hose, holes were afterwards drilled through the safety-lock door, and the water was drawn off into the shaft and pumped to the surface. The tunnel was re-entered sixteen hours after the occurrence. It was then found that 250 yards of sand and mud had come in. Judging by top water mark, the water had about one-third filled the tunnel. Men were at once set to remove the spoil, and in the meantime there was tipped into the bed of the river

about 250 yards of clay to replace the spoil which had run into the tunnel, as it was found, on sounding the bed of the river, that there was a serious depression immediately over the point where the shield was being driven. The clay was spread over the bed of the river from this point to low water line on the Cheshire side, to strengthen the ground through which the shield was subsequently to be driven.

The sand was removed from the tunnel and work resumed in eight days, when operations were carried on with the top horizontal strip in position, leaving the two bottom strips off. When the shield approached within about 15 feet of the Cheshire shaft, the second strip was put on with a board underneath it, thus reducing the opening through which the material was excavated to about 3 feet 9 inches by 12 inches. From time to time the runners were driven forward, as the ground at this point proved to be very broken and treacherous, and the lid of the receiver was kept half pushed over. The work was continued cautiously, until the steel points struck the timber closing the opening in the Cheshire shaft. As the ground now proved to be very much better, the timber was taken out and the shield pushed forward into the shaft; and thus the difficult work was completed on March 22, 1892. From the time the Corporation took over the work, on November 12, 1891, the distance traversed was 618 feet, so that the average speed was 34 feet per week; but, as has been shown, there were periods during the 18½ weeks when difficulties compelled a suspension of driving operations. The greatest distance driven in one week was, as previously mentioned, 57 feet.

The end of the shield, at the bottom, became jammed against the tunnel during the operations, and the plates forming the skin split longitudinally and also crosswise up one of the joints. These plates had to be cut out and loose plates inserted in about 2 feet widths, extending from the back of the rams to the tail of the shield, and attached to the circular girder by studs. These ten plates were simply laid side by side, and they kept the material back, although a small quantity of water drained in through the loose joints. The loose plates, however, prevented any jamming.

After the work had proceeded about three-fourths across the river, the

shield suddenly developed a tendency to twist, and although a 24-foot rail was used as a lever to prevent it from doing so, it was found by the time the Cheshire shaft was reached that it had revolved a foot.

Pressure in the Tunnel, &c.—The air pressure in the tunnel at the commencement was maintained at about 17 lb. to the square inch, but, as the work advanced towards the Cheshire side, it was gradually decreased, the minimum being 10 lb. The highest pressure used was in the work of enlarging the Lancashire shaft, when it reached 25 lb. above the normal pressure, or nearly three atmospheres. The amount of the pressure in the tunnel depended almost entirely on the nature of the overlying strata. A variation of the head of water above the tunnel of 7 lb. due to a spring tide only made a difference of 2 lb. in the tunnel. The pressure of air in the tunnel was often only half that due to the head of water.

Prior to the fixing of the teeth to the cutting edge of the shield, the hydraulic pressure on the rams had often exceeded 4,000 lb. to the square inch; but after the teeth were fitted, it was not found necessary to have a pressure exceeding 3,000 lb. Most of the work was done with a pressure of a little over 2,000 lb., and in an exceptional instance it was as low as 1,100 lb. After the inrush a constant pressure was maintained on the rams, so that it might almost be said that as each shovelful of spoil was got out the shield moved forward.

The work in the tunnel was carried on by seven excavators in each of two shifts, in addition to the two men who managed the locks and those running skips, and it is interesting to note that some measure of competition asserted itself, the day men competing with the night men as to which shift should drive the greater distance. The shield was driven forward in lengths of 18 inches, the time on one occasion being but fifty minutes, and then a ring of segments was put into position. Another squad of men followed up, caulking the joints with cement. The cement was mixed with a very small quantity of water—it was hardly damped, in fact. It was then caulked into the joints on exactly the same principle as in the case of iron borings and sal-ammoniac. This caulking was only done to within about 3 feet of the bottom level of the tunnel, the

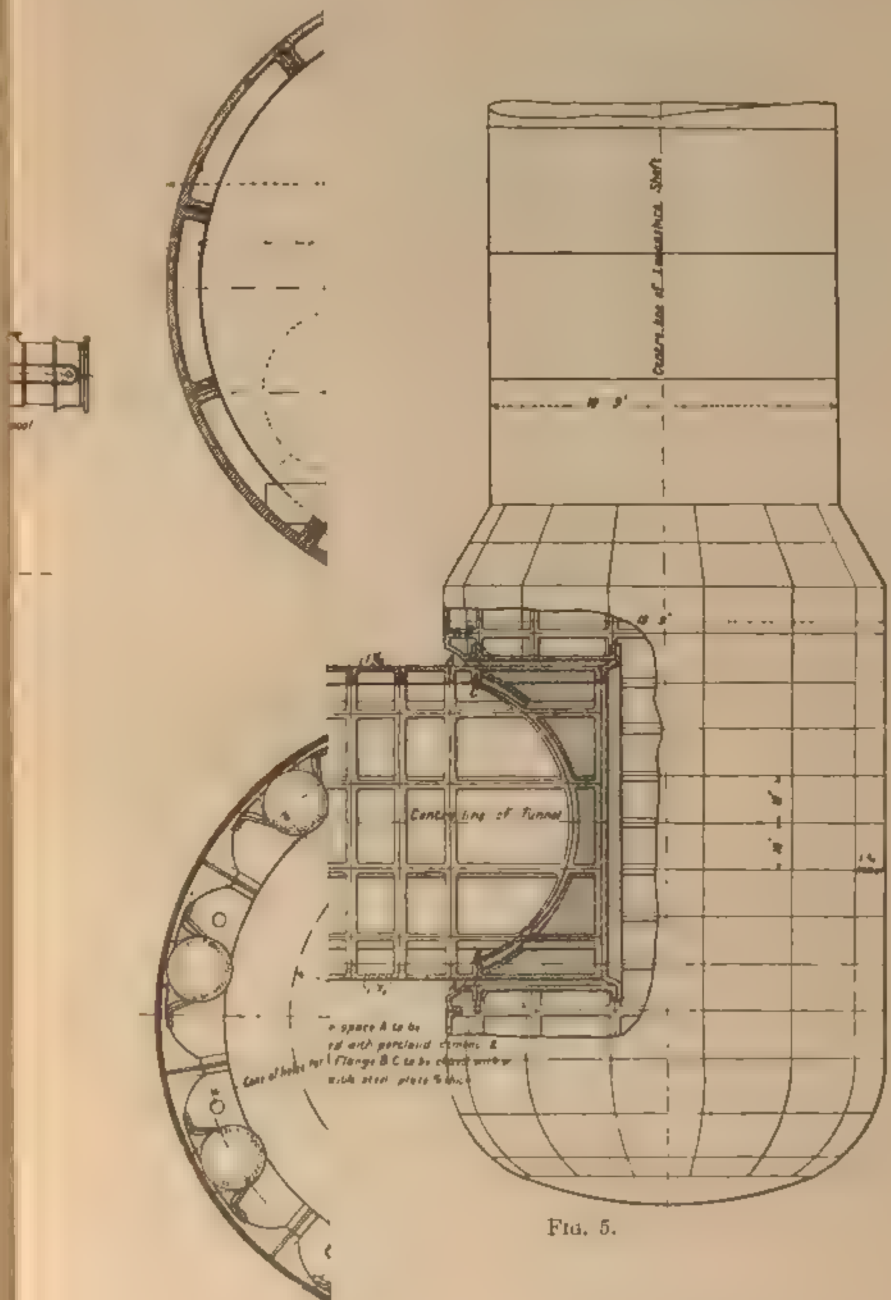


FIG. 5.

Between pages 464 and 465

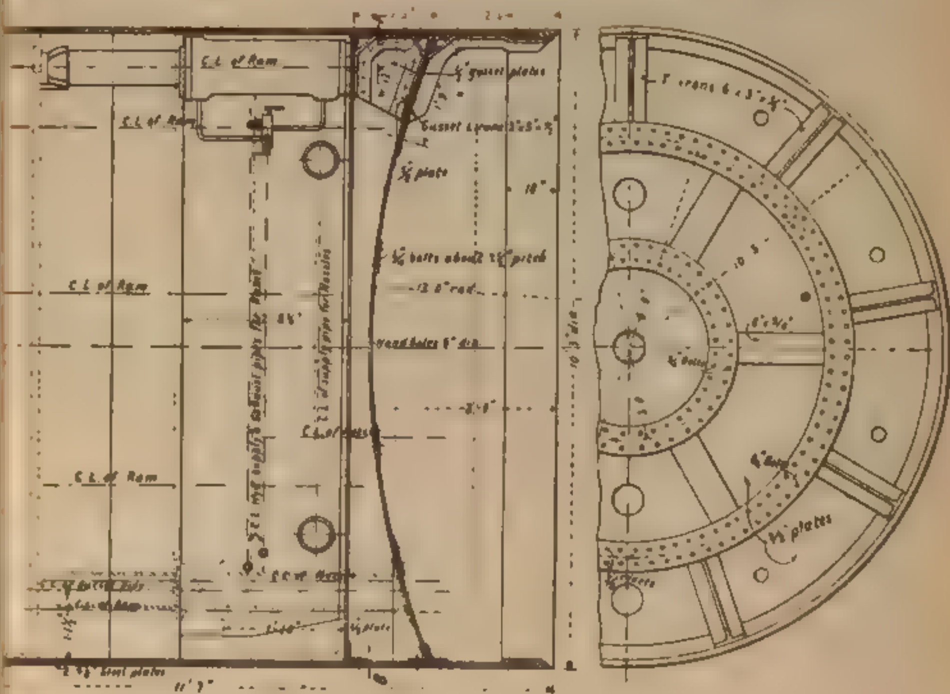


FIG. 9

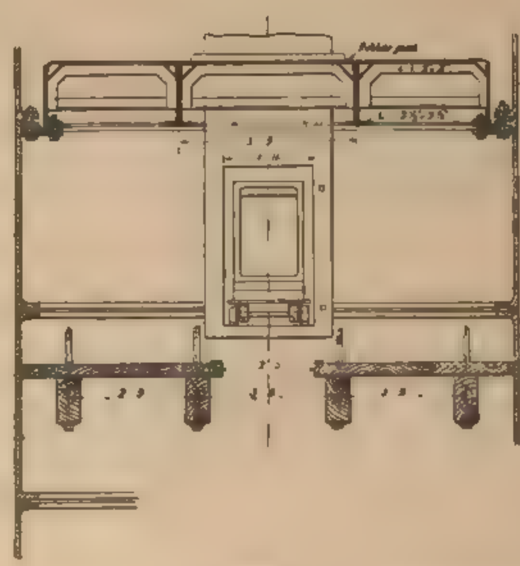


FIG. 11

[Between pages 464 and 466.

remainder being filled with spoil for the supporting of a railway for the removal of the spoil. The material was taken away on skips run on trolleys on the railway, and after passing through the locks these were lifted up the shaft to the bank by steam cranes. Of course, when the tunnel was completely driven, the remainder of the joints were caulked.

CHAPTER XXXIII.

SUBAQUEOUS TUNNELS (CONTINUED).

THE BLACKWALL TUNNEL UNDER THE THAMES.

THE Bill for the construction of this tunnel was brought before Parliament in 1886–7 by the late Metropolitan Board of Works. There was practically no opposition, and the measure was passed without difficulty. The Bill authorised the construction of three tunnels, two for vehicular traffic and one for foot passengers, as it was considered that it would be advantageous to conduct the up and down vehicular traffic through different tunnels, and to keep foot passengers separate. The original plans were prepared by the late Sir Joseph Bazalgette, Chief Engineer to the Board. It was decided to give preference to the construction of the foot-passenger tunnel; the contract drawings were accordingly prepared, and towards the close of the year 1888 tenders were invited for the construction of a tunnel having an internal diameter of 15 feet. Two tenders were received, and that of Messrs. Pearson & Son, for £318,840, was accepted. About this time, however, the Metropolitan Board of Works was superseded by the London County Council, and in consequence of the feeling which appeared to exist amongst members of the latter body, that the construction, in the first instance, of the smaller tunnel was not a wise course to follow, the sealing of the contract with Messrs. Pearson & Son was at the last moment stopped by the Local Government Board.

The matter was then gone into *de novo*, and the Council went very fully into the question of the best size of tunnel to be adopted, and the opinions of Mr. J. W. Barry and Sir Benjamin Baker were obtained on the subject. In December 1890 Mr. A. R. Binnie, Chief Engineer to the

Council, after consultation with Sir Benjamin Baker and Mr. J. H. Greathead, reported to the Council that a tunnel of 27 feet external diameter was the best size to adopt, and that the bottom of the tunnel should be at such a level that the maximum air pressure required for its construction should not exceed 35 lb. per square inch. Fresh drawings were then got out and tenders invited. Six tenders for the work were received, and Messrs. Pearson & Son were again successful in obtaining the contract, the amount of their tender being £871,000. The construction of the tunnel was commenced in 1892 by the London County Council, Mr A. R. Binnie, M.Inst.C.E., the Chief Engineer to the Council, being responsible for the work. Messrs. David Hay and Maurice Fitzmaurice, MM.Inst.C.E., were appointed resident engineers in charge of the work for the London County Council. Mr. E. W. Moir, M.Inst.C.E., is engineer for Messrs. Pearson & Son, the contractors; Mr. E. H. Tabor, M.I.M.E., is in charge of the machinery; and Mr. G. H. Halden, A.M.I.C.E., is responsible for the lines and levels in the tunnels.

A general plan of the work is given in fig. 1, Plate XXIX., and fig. 2 is a small scale section which shows the lengths of the various kinds of work and gradients of the approaches. It will be noticed, that the approach on the north, or Middlesex side, commences at the East India Dock Road opposite to the entrance gate to the Docks. From this point, taking a southerly course and passing under the Great Eastern and Midland Railways, close to Poplar station, the roadway to the tunnel descends by a gradient of 1 in 34·384 until the foreshore of the river is reached. At this point it has attained the level fixed upon for the horizontal portion under the river bed.

Passing under the Thames in a south-easterly direction from a point about 50 yards above Blackwall Stairs, the south bank of the river is reached. Here the gradient for the Kent approach commences, the gradient being 1 in 36·194. The surface level is reached in Blackwall Lane opposite the South Metropolitan gas holders. The existing road level on the southern side being lower, it was possible to obtain a slightly better gradient than on the north side. The gradients on both sides are, it will be seen, fairly easy,

and such as it would have been impracticable to obtain in the approaches to a high level bridge, unless they were made about twice as long.

The open approaches, on the Middlesex and Kent shores respectively, are 765 feet and 860 feet in length. The structure is composed of 6 to 1 concrete, faced with brickwork above the footpath level, and bonded to the concrete. The face is glazed, as in the cut-and-cover and tunnel proper to be described hereafter. The face of the retaining wall is battered 1 in $4\frac{1}{2}$ up to surface level, where a Portland stone string course is placed, forming a face for the parapet wall, which is finished with a granite coping. A layer of $1\frac{1}{2}$-inch asphalte is carried through the invert and up the back of the retaining walls, and a staircase 6 feet wide is placed on each side of the roadway, at the ends of the open approaches on both sides of the river.

At the commencement of the open approach on each side of the river, a gauge for maximum height of loads on vehicles is built in the form of an arch, which will support a house for the tunnel superintendent.

The roadway will be 16 feet wide throughout, giving sufficient accommodation for two of the largest vehicles used in the London streets, placed side by side. There will be a footpath on each side of the roadway, 5 feet $4\frac{1}{2}$ inches wide in the open approach, and 3 feet $1\frac{1}{2}$ inches wide in the cut-and-cover portion and the iron-lined tunnel. The roadway is carried by a 9-inch brick arch, which forms the roof of a subway to contain pipes &c., as shown in fig. 3, Plate XXIX. Access to this arch is obtained by a shaft at the end of the cut-and-cover portion on both sides of the river. By this arrangement the necessity of breaking up the road in order to lay pipes, &c., or to repair them, is obviated.

Drainage.—Arrangements are being made for the conveyance of all water collected in the open approaches on both sides of the river to a well in No. 2 shaft, where permanent pumps will be erected to deal with it.

The arched openings forming side entrances to the subway are so arranged that large pipes can be readily passed in. The drainage of the tunnel is mainly provided for by means of pipes laid close to the kerbs. These pipes are carried through the shafts, and are so laid as to clear the cross arches for the side entrance to the subway already referred to. The water from these pipes is collected at the foot of No. 2 shaft, and then

pumped to the surface. Illumination will be by means of the electric light. It is not anticipated that any special measures in the matter of ventilation will be necessary; but the entrance gauge arches are 2 feet less in height than the tunnel, so that, if requisite, a ventilating trunk can be inserted in the top of the tunnel.

Cut-and-Cover.—The section adopted for the cut-and-cover portion on the Middlesex side, being a length of 436 feet, is shown in fig. 4, Plate XXIX. The depth of trench here varies from 34 feet at High Street, to 41 feet at the Great Eastern Railway. A similar section is adopted for a length of 335 feet of cut-and-cover on the Kent side, where the depth varies from 37 feet to 42 feet. The deeper portion of cut-and-cover on this side of the river, extending for a distance of 611 feet south of shaft No. 4, is at a maximum depth of 65 feet below the surface, and is of a heavier section. The thickness of the brickwork is, for the two sections mentioned, 1 foot 6 inches and 1 foot 10½ inches respectively, the inner ring, in each case above footpath level, being of glazed bricks. Immediately outside the brickwork, a band of asphalte 1½ inches thick is placed to ensure watertightness. The brickwork is backed up with 6 to 1 Portland cement concrete, built tight to the sides of the trench as shown. A polished granite moulding is placed at the end of the cut-and-cover arching on each side of the river. The total length of the cut-and-cover portion, which is built of brick and concrete, is 1,382 feet.

Cast-iron Lining for Tunnel.—Two sections of cast-iron lining are shown in figs. 5 and 6, Plate XXIX. The section which is shown in fig. 5 shows the lining which is used between shafts Nos. 1 and 4. This portion is 2,262 feet long. The lighter section shown in fig. 6 is used between shaft No. 1 and the Great Eastern Railway on the Middlesex side. It has a length of 821 feet. The total length of the iron-lined tunnel is therefore 3,083 feet

The heavier section consists of a tube 2 inches in thickness, having flanges 12 inches deep and from 2 inches to 3 inches thick; each ring is 2 feet 6 inches in length, and is built up in fourteen segments, with a solid key at the top. The key is slightly narrower at the outside of the lining than at the inside. This is to facilitate the insertion, when it is required to fix it, and the contiguous flanges differ from the others in being

made to suit it. The weight of each ring complete is $16\frac{1}{2}$ tons. All joints, both longitudinal and circumferential, are machined throughout, and recesses 2 inches by $\frac{3}{8}$ inch are formed on the inside for caulking, as shown on figs. 5 and 6. The segments are bolted together with $1\frac{1}{2}$-inch bolts of the various lengths necessary. Holes $1\frac{1}{2}$-inch diameter are drilled and tapped through the plates (see fig. 5), and grout is forced, by means of compressed air, to fill up any spaces outside the lining. There is an annular space outside the cast-iron lining due to the sliding forward of the shield as each section of the tunnel is complete. The holes are closed by wrought-iron screwed plugs when the grouting is complete.

The lighter section of cast-iron lining, shown in fig. 6, is a tube $1\frac{1}{2}$ inches in thickness, with flanges 10 inches deep and from $1\frac{1}{2}$ inches to $2\frac{1}{4}$ inches thick. In all other respects this lighter section is similar to the heavier lining described above. The weight of each ring complete is $11\frac{3}{4}$ tons, and the outside diameter of both sections is 27 feet. There will be an internal lining of special concrete, 4 to 1, faced with glazed work. The additional scantling in the river portion has been adopted on account of the bad ground, and to provide against contingencies that might arise.

When the work was taken in hand, it was evident that water in large quantities would be met with, not only under the river but also in the approaches, and every attention was given in the designs to insuring water-tightness. Bore holes were taken at frequent intervals to show the nature of the ground to be dealt with, and some of these indicated that ground of the worst possible nature would be encountered.

Shafts.—Four large shafts, of an internal diameter of 48 feet, are placed in the positions shown in fig. 2, Plate XXIX. These shafts are placed where changes of line or level occur, it being considered that a shield of considerable length, such as would be required for this tunnel, could not be made to work round curves; whilst, at the same time, the inconvenience of having special castings for the iron tunnel lining has been avoided.

As the tunnel passes through these shafts, openings have to be made in the latter in order to admit the tunnel lining. These openings are circular, being 29 feet 4 inches in diameter. The shaft is specially strengthened round them to compensate for the loss in the continuity of

the structure. They were temporarily closed while being sunk, large iron shutters or plugs being used for the purpose. These plugs were bolted together, so as to be easily removed when it became necessary to drive the shield through the shaft. The bottom floors of the shafts are composed of 6 to 1 concrete, 14 feet thick, a water-tight skin of iron $\frac{1}{4}$ inch thick being placed near the bottom of the concrete and attached to the inner skin. Spiral staircases will be fixed in shafts Nos. 1 and 4, to enable foot-passengers living near these shafts to enter or leave the tunnel, without having to go to the ends of the approaches to do so. Shaft No. 3 is sunk in property belonging to Messrs. Forbes, Abbott, & Leonard, and as the London County Council purchased only an easement for this and the parts of the tunnel adjoining, no access can therefore be made to this shaft from the surface. It will be covered in by a domed arch, and will carry a ventilating shaft 7 feet 6 inches in diameter.

River Wall.—A river wall has been constructed to enclose No. 2 shaft on the Middlesex side. The construction is of concrete and timber, and calls for no special description. But a considerable portion of the foreshore has been reclaimed by means of this wall, and valuable wharf space has in consequence been obtained.

Method of Construction: Sinking the Caissons.—This portion of the work was commenced in 1892, the contractors being free to commence their labour soon after March 1 in that year. As the ground on the south side was easier to work than on the Middlesex side, it was determined to commence on the Kent side and to drive northwards. The reason for this was that it was concluded that the men would gain experience in the various operations, and so be better fitted to cope with the exceptional difficulties, which it was known would be encountered as the work advanced.

It was, therefore, determined to commence the work by sinking No. 4 shaft, which is the most southern of the four vertical shafts which have been sunk for purposes of construction and to afford access to the tunnel. This shaft is situated about 600 feet from the Kentish bank of the river, at the point where the cut-and-cover method of construction ends and the iron-lined tunnel commences.

The two lower strakes, forming the shoe of the caisson, were delivered

by the makers in three segments, and were placed together on the ground on May 21, 1892. Each of the segments weighed about 9 tons. The first two strakes are of steel, the remainder being iron. The lower portion of the caisson is strengthened by radial diaphragms, some of which extend upwards to a height of 48 feet 6 inches from the cutting edge, and thus serve to strengthen the structure of the caisson, where its cylindrical form is interfered with by the tunnel openings on either side.

Each shaft consists of a wrought-iron caisson, 48 feet in internal diameter, and of 58 feet external diameter at the bottom. The plates of which they are constructed vary, from $\frac{3}{4}$ inch at the cutting edge to $\frac{5}{16}$ inch at the top, and are braced together with angle irons. The plating is so arranged that the inner skin of the shaft is plumb, whilst for the outer skin the rings of plating are placed telescopically. That is to say, the inner skin plates are placed at a slight angle from the vertical, so as to counteract the batter that would be given to the whole skin by the overlapping edges of the plates; while in the outer skin, on the other hand, the plates are vertical, and as they overlap, there is a batter on the outside of about 1 in 100. This materially decreases the skin friction in sinking. At a distance of about 8 feet 6 inches from the bottom, the inner skin is bell-mouthed to meet the outer skin, and thus forms a cutting edge for the purpose of sinking. This cutting edge is strengthened by an external steel band 2 feet deep by 1 inch thick.

The space between the outer and inner skins of the caisson, varying from 5 feet at the bottom to about 4 feet at the top, is filled with cement concrete of 6 to 1; and in this way a solid cylindrical structure of great strength is formed. A perspective view of this caisson is shown at a later stage of construction in fig. 7, Plate XXX.; the openings through which the tunnel roadway will pass, and which are closed whilst the caisson is being lowered, are here shown. The method of closing these openings prior to sinking (of which a general idea will be gained from fig. 10) is as follows: iron plates, forming a continuation of the outer skin, are bolted together and backed by horizontal and vertical girders bolted to the sides of the opening. Bolts were used in lieu of rivets for this portion of the work, in order to facilitate the removal of the plugs when the tunnel

shield arrived at the shaft. The radial stiffeners used between the two skins are shown in fig. 8, a part sectional plan on the line A A (fig. 10), above the opening. Fig. 9 is a part sectional plan at the line B B (fig. 10). The stiffeners are placed above and below the opening; the hood, or collar, which forms a prolongation of the tunnel opening is supported by brackets or cantilevers. The junction between the iron lining of the tunnel and the vertical shafts is formed by means of special castings. The cellars, or projecting hoods, are attached to the inner skin of the shaft, and the special tunnel lining castings are used at this part. A joint is effected by the whole being substantially bolted together and made water-tight.

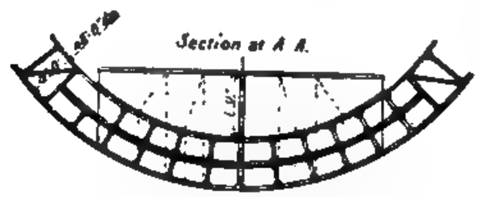


FIG. 8.

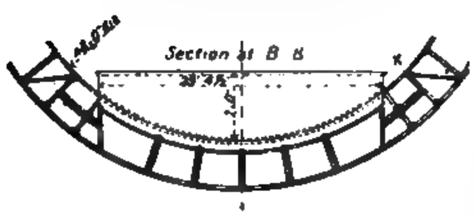


FIG. 9.

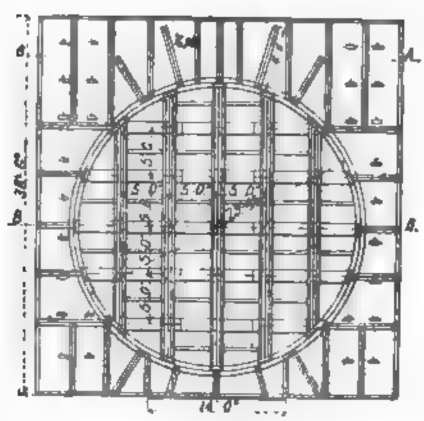


FIG. 10.

Concrete, 4 to 1, is used as packing between the cast-iron tunnel lining and the projecting hood, or collar. Dependence is not placed on the concrete to keep out the water, but on the end plate; the joints between the plate and the lining, and those between the plate and the collar, being securely caulked.

The opening while sinking the caisson is closed by a plug, or shutter, as already mentioned, fitted on the outside by cover plates. These are used for the purpose of strengthening the connections between the girders and the outer skin, where strips of wood are used as packing pieces for the purpose of allowing some latitude in the fitting, in order to enable the parts to be taken down and used over again.

The method adopted in connection with the sinking of No. 4 shaft was by excavation from the interior, freeing the cutting edge, and building up

the caisson as it sank down. As the operation proceeded, the concrete was filled in between the skins of the caisson, in order to give the requisite weight. The sinking was first through made ground, then, successively, through loamy clay, peat, ballast, and London clay, and finally through sandy clay. No special difficulties were encountered, as, owing to the pumping operations which were being carried on in the cut-and-cover works in the rear, the soil was fairly well drained, and there was almost entire freedom from water. Owing to the ground being softer on one side than the other, especial care was necessary in keeping the caisson in an upright position at the last part of the sinking. This difficulty was surmounted by freeing the cutting edge on the side where the soil was hardest, and by weighting the caisson judiciously. There was a good deal of water in the sandy clay at the bottom of No. 4 shaft, which was at a depth of 78 feet below high-water mark. This portion of the work being at a lower level than the cut-and-cover work, it was not relieved in the manner already alluded to. Some pumping had, therefore, to be done in order to keep the bottom of the shaft clear of water whilst the concrete was being laid.

This No. 4 shaft was sunk entirely in the open; but arrangements were made for the insertion of an air-tight floor, in case trouble might have arisen through water entering and the use of compressed air be necessary. This air-tight floor was used in connection with the other shafts. The floor consisted of $\frac{5}{8}$-inch buckle plates riveted to the top of 18-inch girders, which are attached to the sides of the caisson. To give additional strength, there are above ten girders, 4 feet deep, which are at right angles to the lower girders, and these are crossed by two 12-foot girders. This air-tight floor is placed higher than is usual in caissons used for bridge foundations and similar purposes, owing to the fact that provision in this case had to be made for the use of air in the construction of the tunnel itself, and that the floor would in that case serve as a cover, when the shield used in the construction of the tunnel was being driven through the shaft.

When the work of sinking the shaft was completed, it was necessary to shut out the water, which rose through the sandy clay at the bottom, to prevent injury to the concrete bottom. This was done by allowing it to escape through a pipe leading through the concrete and water-tight floor

into a sump, whence it was pumped to the surface. A valve was placed in this pipe, which was closed when the concrete had set, thus shutting the water out finally. The sinking of the No. 4 shaft occupied nine months.

The boring of the tunnel was performed by means of a shield, a description of which is appended; but it may be here mentioned, that the difficulty of the work was much increased owing to the porous nature of the soil composing the river-bed, and the proximity of the top of the working to the river. In one part of the work only 5 feet 2 inches of sand and gravel intervened between the crown of the working and the Thames, and a considerable quantity of clay was thrown into the river from barges in this and other spots, in order to form as far as possible an impervious layer on the top of the gravel.

General Description of the Shield.—The shield used at Blackwall is based on the original patent of Sir Marc Isambard Brunel, dated 1818, in which he specified and set out in drawings a semicircular wrought-iron shield, cut up into working spaces or pockets, the rear or tail of which overlapped a cast-iron tunnel 20 feet in diameter, the shield being thrust forward by hydraulic jacks. In designing the Blackwall shield, advantage was taken of others which had been patented subsequently to 1818; amongst them that of Mr. Peter Barlow, dated 1864. There is considerable similarity also between the shield used and that which was adopted by Mr. Joseph Hobson, the engineer of the Great Western Extension of the Grand Trunk Railway of Canada, at the Sarnia Tunnel, under the St. Clair River.[1]

The shield used was made by Messrs. Easton & Anderson, of Erith. It is 19 feet 6 inches over all, is 27 feet 8 inches in external diameter, and is composed principally of an outside shell made up of four $\frac{5}{8}$-inch steel plates. An illustration of this shield is given in fig. 11, Plate XXX., which shows a longitudinal section, with the method of operation and the men at work. The interior space is divided, as shown, into a front and back portion, by two diaphragms, consisting of vertical plates. These diaphragms are made air-tight, in order that pressure of air can be maintained at the working face in excess of that required farther back.

[1] Many of the improvements in the Blackwall Tunnel shield have been patented (1891) by Messrs. S. Pearson & Son, the contractors for the tunnel.

Up to the present time, however, this differential air pressure has not been found necessary. The air locks are formed, as shown, in the space between the two diaphragms, the doors provided being faced with india-rubber. The material excavated is carried through the diaphragms by the shoots, which are also provided with doors, and thus form air locks. The part in the rear of the first diaphragm is generally described as the tail of the shield. It consists of a built-up skin of plating. In front of the diaphragm there is a second or inner skin as well; both of these skins are strongly fastened to each other, and thus form a structure of considerable strength and stiffness. The two skins are brought together to form the cutting edge. The shield is divided horizontally by three platforms, thus affording four platforms or stages from which the working face can be attacked. There are also three vertical partitions which act as stiffeners. There are thus twelve compartments, into which the front part of the shield is divided. On reference to fig. 11, it will be seen that between 6 and 7 feet in the rear of the cutting edge there is a vertical screen depending from the top of each compartment; the space inclosed between this hanging screen and the diaphragm forming the front of the air lock is a safety chamber to which the men can retreat in case of a sudden irruption of water from the face. The water will not rise to the top of this inclosed space, owing to its being occupied by the imprisoned air. The men would thus be able to stand with their heads out of water, until they were able to make their escape through the air lock. Sliding iron shutters are used when working in gravel, which are pushed forward on guides provided for the purpose by means of screws, to support the face after excavation. The guides are shown in fig. 12, Plate XXX., in which, as in the adjoining figs. 13 and 14, details of the construction of shield are shown.

Lowering the Shield to position. The total weight of the shield, which had been got ready whilst shaft No. 4 was being sunk, is 250 tons. A dock was excavated in the earth close to the mouth of the shaft, and in this the shield was built. When the erection was completed the two ends were closed in by timber, so that the whole structure would float. The dock was then connected with the top of No. 4 shaft, a part of the caisson

being temporarily removed for that purpose. Water was then admitted to the dock, which at the same time filled No. 4 shaft, and the shield was floated out of the dock until it was in the shaft. The water was then removed from the shaft by pumps, and the shield gradually descended, until it reached its proper position for commencing tunnelling operations at the bottom of the shaft. This stage of the work is illustrated by an engraving, fig. 15, Plate XXX., which shows the shield on the point of entering the earth, the engraving being from a photograph taken by so arranging the camera that the lens was pointed down the shaft.

Driving the Shield forward.—The shield is moved forward, as the material is excavated, by means of hydraulic rams placed in the rear. These are illustrated by fig. 16. The finished segments of the cast-iron tunnel lining form an abutment, against which the rams push in driving

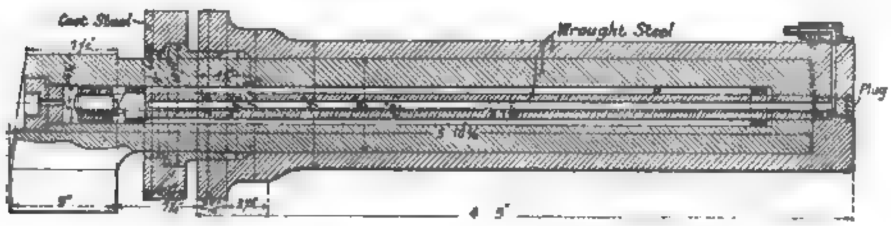


FIG. 16.

the shield forward. The head of the ram is bevelled off, so that the pressure may bear against the cylindrical part of the lining and not on the flange, which might thus be broken off. The rams are each 8 inches in diameter and are twenty-eight in number. The hydraulic pressure being 2 tons to the square inch, a thrust of about 100 tons is exerted by each ram. The total pressure available for the work of pushing forward the shield is, therefore, about 2,800 tons. This has at times been exceeded, the hydraulic pressure having on occasions been increased to $2\frac{3}{4}$ tons per square inch, a total pressure of 3,850 tons being thus exerted. The rams are arranged to enable them to guide the shield, and thus to correct any deviation that might result from inequalities in the soil or other causes. This is effected by shutting off the necessary number of rams on either side; but some trouble has at times arisen, owing to the power of the

rams remaining under pressure being insufficient to drive the shield forward. These difficulties have, however, not been serious, and the line of the tunnel has been practically maintained.

Erection of the Lining Segments.—The cast-iron segments which form the tunnel lining are erected inside the shield and there fixed together, the tail of the shield thus surrounding the last ring of lining put in place. This is shown on fig. 11. The following ring of lining is then erected inside the shield tail, and the shield is pushed forward by the rams as the work proceeds, and the erection of the rings is complete. For the purpose of putting the heavy iron castings in position (each segment weighs about 1 ton), two hydraulic erectors are used. These lift the segments to their place and hold them there, until they are securely bolted to the adjacent segments.

When tunnelling was first commenced from the bottom of No. 4 shaft, the face for about 2 feet at the top consisted of ballast which had been drained by the pumps already referred to. There was about one foot of sand at the bottom, but the rest of the face was hard clay. Under these circumstances, it was found possible to go some distance without using compressed air. It was known that the top of the tunnel would pass out of the ballast in a short distance, and it was therefore decided to drive a small top heading in advance of the shield, timbering being used for the purpose in preference to the sliding iron shutters previously mentioned. This method of working was found to answer very well. It was possible to deal with the water, but the timbering was required to prevent the ballast being washed in, and no other timber was used. The ballast, it may be mentioned, was only on the top, the rest of the working face being clay.

The first permanent ring of the tunnel was erected on June 9, 1893. The shield was then working down a gradient of 1 in 36. The beds of clay and sand were nearly horizontal, so that the ballast at the top of the tunnel gradually disappeared, whilst the sand at bottom gradually increased in depth. After the shield was working altogether in clay, some difficulty was experienced, owing to the thin clay at the top being insufficient to prevent a large quantity of water finding its way through from the ballast overhead into the workings and penetrating between the tail of the shield and the

cast-iron lining. During the first two months' working a length of 125 feet was completed, fifty rings having been put into place. At this point, the cutting edge of the shield came in contact with some hard substance, and was bent up. Seams of shelly rock were here found at the bottom of the clay. The deformation was not considered sufficiently serious to stop the work, and the shield was still driven forward, care being taken to complete the excavation in front of the damaged part. Work was continued in this manner until 192 feet = 77 rings had been completed. This brought the work up to about the middle of September 1893, the damage to the cutting edge of the shield having first been noticed some six weeks previously. The damage to the shield was now found to be so serious that it was necessary to entirely relieve that portion of the shield from pressure. It was impossible to repair the shield *in situ*, and, as it was also impossible to draw it back to its starting point at the bottom of No. 4 shaft, the only alternative was to keep it going until it reached the bottom of the next shaft. This was No. 3, situated close to the river bank. The difficulty was eventually overcome by driving a bottom timbered heading about 50 feet in advance of the bent portion of the shield; and by laying down in this a concrete bed of the same shape as the bottom of the shield, there being about 2 feet of sand here at the bottom. On this bed the shield slid forward impelled by the rams, and in this way the injured portion of the cutting edge was relieved of work. The progress here was at the rate of about 5 feet in twenty-four hours. Unfortunately the depth of sand continued to increase, the shield being driven through the horizontal bed of clay at an incline; and a considerable body of water forced its way through before No. 3 shaft was reached. It was discovered that there was connection between the water in the shaft and the water in the tunnel, and that the water in the tunnel was reduced when blows of water and sand occurred under the cutting edge of No. 3 caisson, which was then being sunk to form the shaft. By the middle of December, 477 feet of the tunnel had been completed, 191 rings having been erected. The shield had by this time worked so far down that the sand was up to the middle of the shield, and the water had

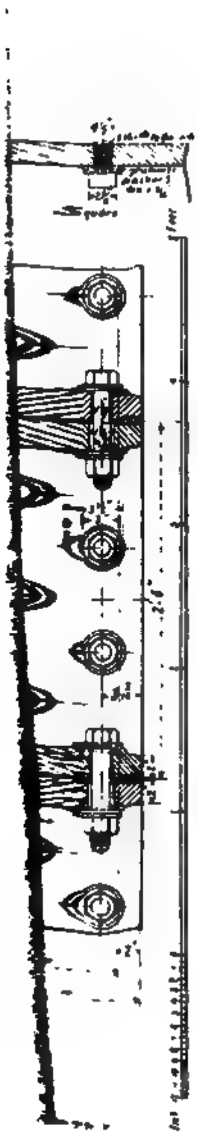
become very troublesome. On December 16 there was a heavy rush of water and sand into the heading that was being driven in advance of the tunnel, so that it soon became full of sand. At this time the cutting edge of the shield was only 67 feet away from the side of the caisson of No. 3 shaft, the face of the heading being 30 feet in advance; whilst the caisson which was then being sunk had its cutting edge 4 feet higher than the bottom of the tunnel heading. The back of the shield was therefore timbered up, and the water rose to a height of 15 feet in front of it.

Further progress was for the time abandoned, as it was considered to be dangerous to advance the tunnel further in the direction of No. 3 shaft until the latter was sunk to its full depth; and it was determined to carry on the operations by the aid of compressed air. A brickwork bulkhead was therefore built across the tunnel, air locks being provided; there were two air locks at the level of the temporary roadway in the tunnel, and a third. a smaller one, above, to be used in case of emergency.

On March 14, 1894, No. 3 caisson was sunk to its full depth, and on the 23rd of the same month compressed air was forced into the tunnel. No further trouble was experienced from water. The heading was cleared from sand, and the timbering was found to have been very little injured. An air-tight floor had been built in the caisson of No. 3 shaft, similar to that referred to in the description of No. 4 shaft. The tunnel heading was now continued to No. 3 shaft, and the shield finally reached the shaft at the beginning of May 1894.

The greatest pressure of air used in this portion of the work was 22 lb. to the square inch. When the shield was once within No. 3 shaft, access to the injured portion of the cutting edge was readily obtained and the necessary repairs were executed. The damaged part was cut away, steel castings being substituted. The construction was also strengthened in several respects. These repairs occupied some considerable time, and four months elapsed before it was possible to start driving northward under the river from No. 3 shaft.

Subaqueous Tunnelling.—This portion of the work was commenced in September 1894, and was successfully completed in September 1895. The



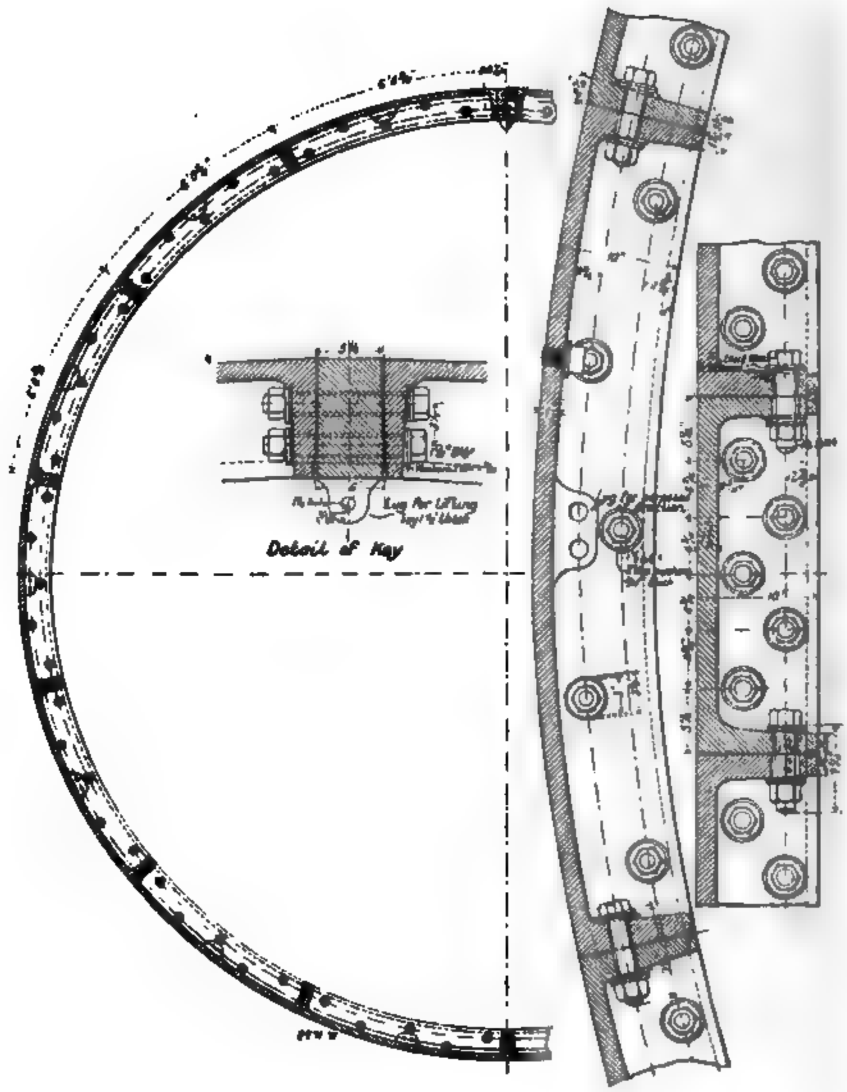
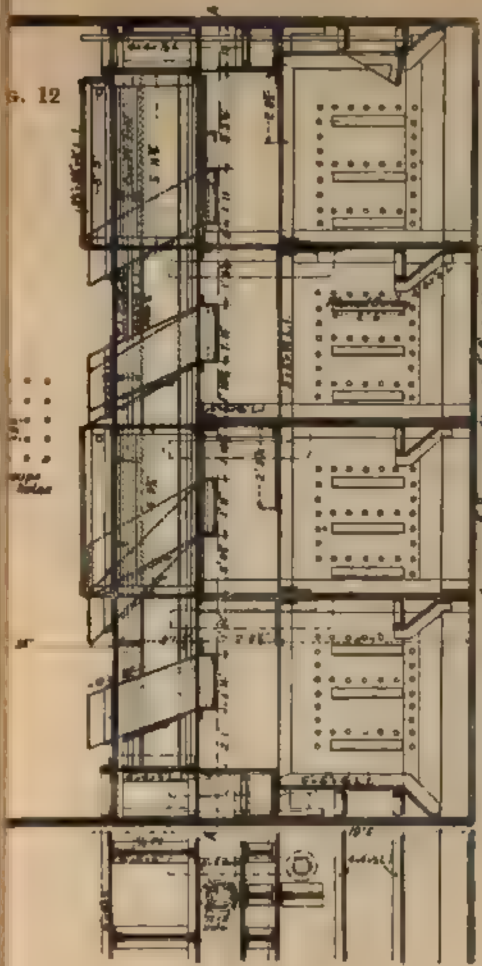


FIG. 6.

[Between pages 480 and 481.



G. 12

Half Elevⁿ Atmosphere side A

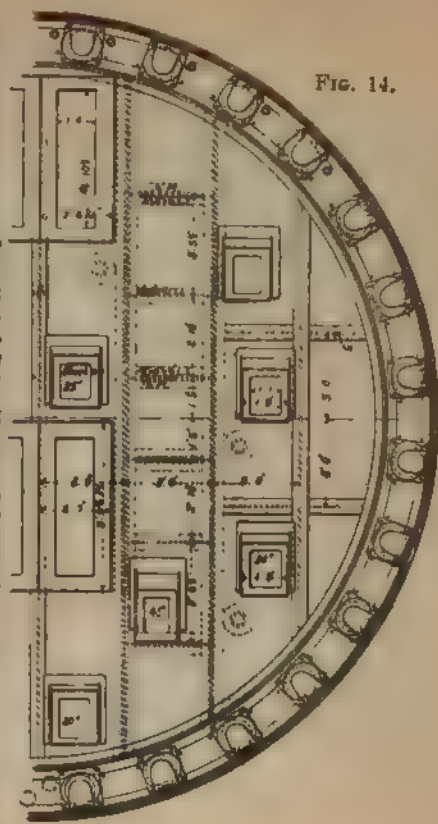


FIG. 14.

FIG. 15.

Between pages 480 and 481.

tunnelling is being carried on from the south side only. For the first 700 feet, out of the total of 1,212 feet of subaqueous tunnel (measuring from centre to centre of the two shafts on either river bank), the work was easy and the progress rapid, the soil consisting mainly of loamy sand and clay. The air pressure ranged from 20 lb. to 26 lb., and as much as 250 feet of tunnel were completed in one month. The effect of the tidal water was hardly noticeable when under the clay, but water came up from the land below, and for this the compressed air was required. After 700 feet of tunnel had been constructed, ballast in direct communication with the river was worked into, and the difficulties were at once greatly increased. The compressed air began to escape very rapidly, so that the supply had to be greatly increased, the stand-by compressors which had been provided for that purpose being all put to work. The benefit of the artificial bed of clay which had been thrown down by hopper barges now began to be felt. This covered the river-bed to the depth of 10 feet, and extended 75 feet on each side of the tunnel line. This largely checked the escape of the air, and gave protection against sudden runs of ballast into the shield, as if a run commenced, the clay came down and choked it. There was only about 5 feet 2 inches of sand and gravel above the crown of shield at this point of the tunnel.

At the present time (March 1896) the work has been some four years in progress, and the portion of the tunnel from No. 4 shaft to midway between shaft No. 2 and shaft No. 1 has been completed. The total length of the tunnel and its approaches when completed will be 6,200 feet, of which 1,735 feet consist of open approaches. It will possibly be a year yet before the work is complete and the tunnel open for traffic; but subaqueous work is always uncertain, and completion may be delayed beyond the time named. The four shafts will be 98 feet (two), 76 feet, and 75 feet deep; and the depth from high-water level to the bottom of the tunnel will be 80 feet, which is equivalent to an air pressure of 35 lb. to the square inch. This pressure, though high, is not beyond the endurance of men suitably constituted for such work.

CHAPTER XXXIV.

SUBAQUEOUS TUNNELS (CONTINUED).

THE GLASGOW HARBOUR TUNNEL UNDER THE CLYDE.

BY the opening of the Glasgow Harbour Tunnel there has been provided a means of cross-river communication under the middle of the harbour which has long been required. The necessity has been recognised for at least twenty years, for in the district of Finnieston there are still, as there were thirty or forty years ago, extensive engineering works, many of them owned by shipbuilding firms, whose yards are farther down the harbour on the opposite side of the Clyde, where, also, the new Cessnock docks are now being completed. The only means of sending manufactures across was by making a detour round by the Glasgow Bridge, a mile to the east. Indeed, Glasgow stretches on either side of the river about four miles west of this bridge; and the traffic over it has been so great that a new structure of greater width had to be taken in hand. The building of a bridge a mile further west at Finnieston, the site of the new tunnel, has long been discussed, but as all the Channel, and some of the deep-sea steamers load between Finnieston and Glasgow Bridge, there were difficulties, which need not here be gone into in detail. But amongst the schemes suggested were high-level bridges, with roads on gradients, hydraulic hoists and spiral ascents, semi-high-level bridges, with swinging spans, swing bridges, &c. The principal objection to the adoption of the swing bridge was, of course, the interruption of the steamer traffic on the river whilst the swing bridges were closed, and to the vehicular traffic when they were open. The high-level bridges were

condemned on account of the length of the approaches. A scheme for the construction of tunnels was prepared by Messrs. Simpson & Wilson, which received the authority of Parliament in 1890. Work was commenced shortly afterwards. Subsequently the Clyde Trust constructed an elevating ferry steamer, called the 'Finnieston,' which, although satisfactory, is open to the objection that the means of communication which it affords is intermittent. The tunnel has not this objection, and will, therefore, meet a long-felt want. The contract for the tunnelling work was placed in the hands of Messrs. Hugh Kennedy & Sons, of Partick; and a complete set of hydraulic hoists has been erected by the American Elevator Company, the work of fitting the girders for them having been carried out by Messrs. Findlay & Co., Motherwell.

There are three tunnels, which are shown in plan as well as in section in figs. 1 and 2, Plate XXXI. A separate subterranean passage having been constructed for the vehicular traffic going south, and one for traffic going north. The central tunnel is for foot passengers only. Both the tunnels for vehicles are shown, with their connection to the shaft, in fig. 3. It may be explained that the apparent distortion of the arches of the tunnels in fig. 3 is due to their meeting the curve of the shafts.

There is but two feet of space intervening between each of the three tunnels across the river. The diameter of that portion of the tunnels which is under the river is 16 feet; it is made up of cast-iron segments; the tunnel under the quays, where the soil is boulder clay, is built of 5 rows of brick arching, and is 18 feet in diameter. At their highest points, the tunnels are 15 feet below the bed of the Clyde, thus leaving ample room for future dredging operations, and 35 feet and 46 feet, respectively, below low and high-water levels. The shaft on the north side is about 400 feet west of Finnieston Street and 170 feet from the quay wall. The river is 415 feet wide, and the length of tunnel from shaft to shaft is just over 700 feet. Both shafts are round, and 76 feet in diameter. The shaft on the north side of the river is 72 feet 6 inches deep, and that on the south side 75 feet 6 inches deep. In each shaft there are six elevators, three for lifting and three for lowering; but any, or all, can be used either for lifting or lowering

when required. They are for vehicles. The passenger tunnel pierces the shaft 34 feet from quay level, with flights of stairs for approaches. From the shaft it is on a decline of 1 in 3, with steps. The cages for vehicles vary in size due to the curve in the plan of the shafts, the larger being 26 feet long by 8 feet 8 inches wide. They are entered from the street level. The maximum load to be lifted is 12,000 lb. = about 5½ tons.

Sinking the Shafts.—The work of constructing the shafts was begun on February 3, 1890, Mr. Alexander Simpson, jun., being the Resident Engineer under whose direction the work was carried out. The south shaft was first taken in hand. The walls for the greater part of their depth consist of an inner and outer lining of ½-inch cast-iron segments, the intervening space being filled with cement, consisting of five parts of sand and broken stones to two parts of cement. The total thickness is 4 feet. The upper and lower parts of the completed shaft are entirely of brickwork. The upper soil of sand was removed to a depth of 14 feet, when water was reached. A double ring of segments, each of 2 feet depth, was built on a cutting edge; other rings were built and filled with concrete as the excavation proceeded, pumping arrangements being meanwhile commenced to deal with the water. With about thirty men engaged in shovelling the spoil and working night and day, the rate of progress per month was equal to a depth of 8 feet of the entire shaft, meaning 2,000 cubic yards of stuff, and the cost for excavating alone was about 500*l.* Sand was found for a depth of 48 feet, but at this point boulder clay was met with, thus increasing the cost of labour. This bed of clay dipped across the shaft from north to south on a gradient of 1 in 4, and as the work proceeded great care was necessary to keep the shaft plumb. It was, of course, being sunk by its own weight. The north side of the shaft sank more slowly than the south side, the resistance being unequal around the circumference; and the shaft developed a tendency to tilt over to the south, and, in fact, it canted to the extent of over 1 foot from the vertical. The north side was accordingly weighted with several tons of pig iron placed on the top; and by this means the level was restored and retained in the vertical position while excavation proceeded. Water was also poured down the outer circum-

ference of the tubing to reduce the friction, a trench being dug at the surface level for that purpose.

The sinking of the shaft by this means was stopped when a depth of 54 feet had been reached, and it was decided, principally on the ground of economy, to construct the remaining 21 feet 6 inches of brickwork underpinning, instead of iron segments. This part of the work is illustrated by figs. 4 and 5, Plate XXXI. The boulder clay was accordingly taken out in sections of about 20 feet wide around the circumference, the clay standing perfectly plumb without support. The brick lining wall was made 4 feet thick, but sand being found at the south side of the shaft, a row of sheet piling 12 inches by 12 inches was driven down the inner wall of the shaft (fig. 4) right into the boulder clay, in some cases to a depth of 40 feet. These piles were driven in in March 1891, and were allowed to remain in until the end of 1893, to give the sand time to drain. The sand being very fine, all this time was required to part with the water. This delay was possible, as the tunnels pierced the shaft on the opposite side of the circumference. The work of excavating the sand and filling in the brickwork underpinning was done in short lengths, the operation, shown in fig. 5, being most successful. The bottom of the shaft consists of a 2-foot floor of concrete on the boulder clay. This south shaft cost nearly 12,000*l*.

The north shaft differs from that first described in respect that there was no boulder clay, the material encountered being sand from top to bottom, and that of the worst description. The work was exactly the same as at the south shaft for a depth of 17 feet, when water was met with. The iron casing of the north shaft was carried right down to the bottom; the rate of progress, however, was slower, the average being only about 6 feet per month, owing to the amount of water being much greater. The water ultimately dealt with was 1,200 gallons per minute, to which quantity it gradually increased as the excavating proceeded. The first pump was a large Tangye machine; but as the water increased, it was decided to substitute a number of smaller pumps by the same makers, and finally three pumps, each capable of delivering 500 gallons per minute, were taken into use. In all cases the pumps were at the bottom of the excavation, on a

stage supported on piles. When the excavation reached the bottom of the original stage, piles were driven immediately on the outside of the piles of the original stage, the tops of the one being bolted to the bottoms of the other. This process was repeated at the successive depths, so that, at the finish, there was one staging of piles from top to bottom, with a series of diagonal bracing timbers and walings, and with several platforms. The pumps had a maximum lift of from 15 feet to 20 feet, and the head of water reached a maximum of just over 60 feet.

The essential difference between this shaft and that on the other side is, as has already been indicated, that the iron casing in the former is carried to the bottom; the soft ground, too, necessitated a different flooring and foundation. In the process of sinking this cylindrical shaft there was no need to load it. Care, in fact, had to be taken in the opposite direction, as there was a tendency at times on the part of the cylinder to drop, and the segments to part. In consequence of this, it was determined to put in an inner lining in this shaft. This inner lining also consists of iron segments, somewhat stronger in section than the ½-inch cast-iron segments already referred to, concrete being placed between these and the original lining. The upper part of the extra lining was of brick, and this reduced the diameter from 80 feet to 76 feet. A similar inner lining was constructed in the south shaft. Concrete, 10 feet thick, was put in over the bottom of the shaft, and grouting under the cast-iron walls. First a layer of cement bags, each 2 cwt., was put down, and concrete afterwards tipped *in situ* to the required depth, the whole becoming one solid mass. In the centre a sump was left, the only bottom in this case being the cement bags, which make a thickness of 18 inches. The water from this sump passes, with all other drainage, to a corresponding sump in the bottom of the southern shaft, where a permanent pumping installation is provided.

Work on the north shaft was started on April 28, 1890, and finished in July 1891, the total depth of the excavation being 83 feet. The cost was not much more than the amount expended on the southern shaft, as the boulder clay difficulty in the one balanced, in part, the extra expenditure in connection with the wet sand in the other. In the case of both shafts, the

upper portion—viz. that above high-water level in the harbour—is of brickwork.

The two outside tunnels, designed for vehicular traffic, are level from shaft to shaft, being reached by hoists; but the centre one pierces the shafts 34 feet from the top, thence descending by a gradient of 1 in 3, the same level as the outer tunnels being reached just at the quay walls. This arrangement, with stairs in shaft and incline, obviates the necessity of lifts for passengers. As to the materials through which the tunnels were excavated, boulder clay extends from the south shaft about one-third across the river bed, and this allowed a splendid start to be made with the boring of the tunnels from this end. The lining is of brickwork, the internal diameter being 18 feet as far as the quay wall, where the iron-lined tunnel is 16 feet in diameter. The iron lining of the tunnel is made up of segments 4 feet $\frac{3}{16}$ inch long bolted together. This difference in diameter was arranged so that the shield for the latter could be easily taken through. Although the boulder clay extended into the bed of the river to a distance of 160 feet beyond the quay wall, it was considered desirable to begin the iron tunnel under the quay wall, and there also to start working under compressed air.

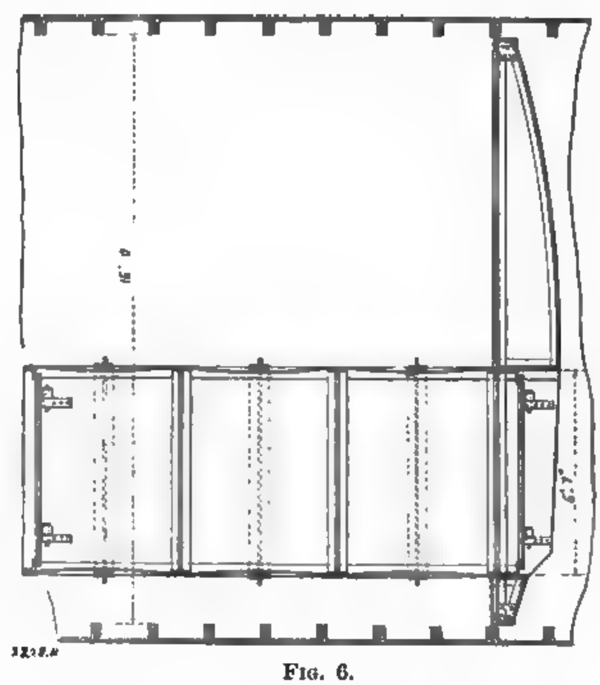


Fig. 6.

Air Locks and Shields. The air locks and shields may now be described. The first air-compressing engine in use was supplied by Messrs. John Slee & Co., Earlestown, Newton-le-Willows. The steam cylinders were 24 inches in diameter, and the air cylinders 26 inches, the stroke being

3 feet. The air valves are practically noiseless when working at a piston speed of 300 feet to 350 feet per minute. Steam was supplied from three Lancashire boilers, working at a pressure of 70 lb. per square inch. There was a large air receiver placed at the bottom of the shaft, as shown in fig. 4. There were two types of air locks used. In the one case the whole area of the tunnel was closed in with brickwork,

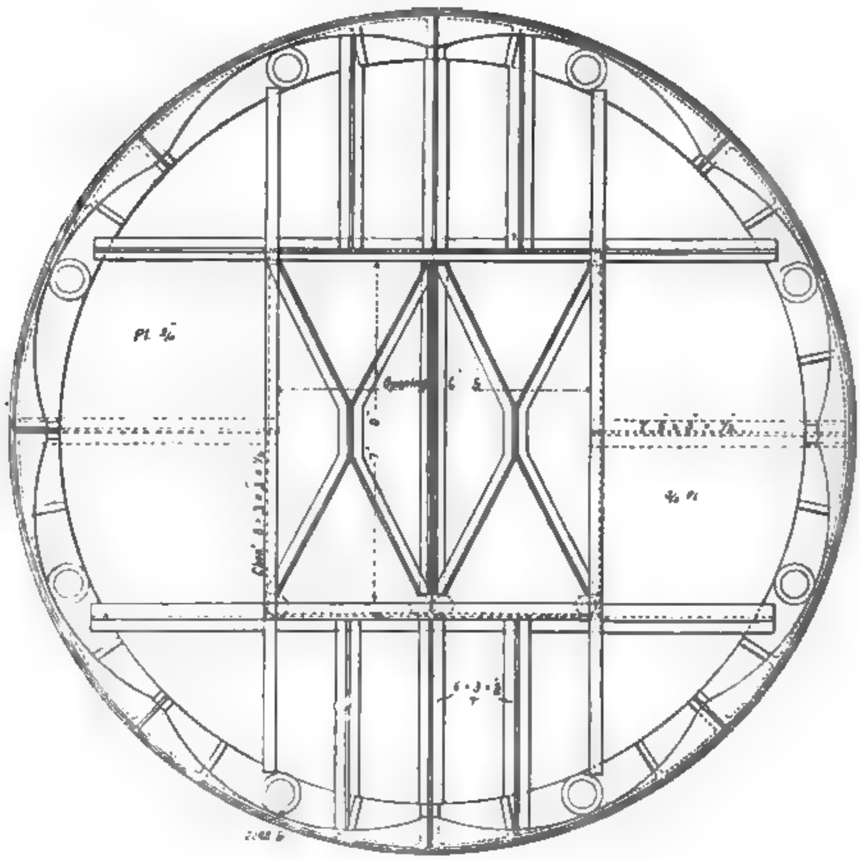


FIG. 7.

with the exception of a passage 5 feet high by 3 feet 6 inches wide, the length being 19 feet. Buckled doors of cast iron, 1 inch thick, fixed to the cast-iron frame were fitted to either end, and made airtight by india-rubber bands. These doors are 3 feet 10½ inches by 4 feet, secured by two hinges, and with 8-inch framing. The necessary pipes were laid through the solid brickwork. The other lock is entirely of iron, and is shown on

fig. 6. It consisted of an iron bulkhead stiffened by vertical beams as shown, while the lock was 5 feet 7 inches by 4 feet 2 inches, and was built up of dished plates. This lock was constructed by Messrs. Fullarton, Hodgart & Barclay, of Paisley.

The pneumatic shields are also illustrated on figs. nos. 7 and 8 (below) and by no. 9, Plate XXXI. The shield first used is shown by fig. 7. The outer shell was 17 feet 3 inches in diameter, and measured 7 feet from the cutting edge to the back. It was built up of two thicknesses of

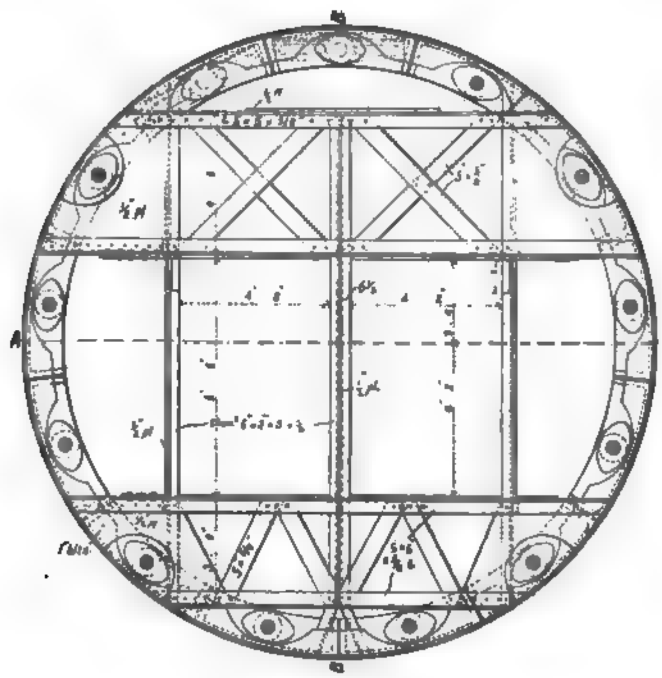


FIG. 8.

steel plates, each $\frac{3}{8}$ inch thick, double riveted. There were four plates to the diameter of the shield. The cutting edge projected about a foot in front of the diaphragm. When a shield was required for the second tunnel, modifications were made on this first design, principally in the direction of strength, although during the construction no incident developed to make this other than a precautionary measure. The later design is illustrated by fig. 8. The outer shell was the same, 17 feet 3 inches in diameter, but it measured 8 feet 6 inches from cutting edge

to back. The cutting edge had a stiffening ring on the diaphragm. There were two sliding doors 6 feet by 4 feet 2 inches, but it was at no time found necessary to close them. Inside the diaphragm there was at the top and bottom a girder for stiffening the shield. This arrangement is shown in fig. 9. On the platform there were two hand pumps, as shown, for working a series of thirteen small hydraulic rams, 7 inches in diameter, with a stroke of 2 feet. Immediately behind the diaphragm was a series of cast-iron segments, abutting against each other and forming a complete circle. The hydraulic cylinders were bolted to these, and through the skin plating of the shield. For grouting behind the tunnel plates, there was a grouting pan about 2 feet 6 inches by 18 inches. From this pan there was a hose pipe with an iron end-piece and nozzle. The grouting was done under a pressure of 50 lb. to the square inch. Both shields were made by Messrs. Markham & Co., of Chesterfield.

The west tunnel was first started, and about 60 feet driven without the use of air pressure or shield. The compressed-air plant was started on June 1, 1891, but as long as the work was through boulder clay little pressure was required. The experience gained throughout the work was, it may be stated, that the rate of progress was not affected by the fact that the men had to work under pressure—the pressure, however, seldom exceeded 10 lb. When the men were working without air pressure, the progress was 12 lineal yards for the first month, May, and for the June following, when the pressure was first used, 14 lineal yards; in July it was 17 yards. In August, when operations were half in clay and half in sand, the progress was 19 yards a month, the average in the sand under air pressure was about 20 yards a month. The air pressure varied greatly, from 18 lb., when the sand was first reached, to $2\frac{1}{2}$ lb. when the north shaft was reached. The highest pressure was reached when crossing the middle line of the river, when there was a little wet sand. At high tide there was a head of 60 feet, and at low tide of 50 feet. Reducing valves were fitted on the air pipes.

The east tunnel was started from the south shaft, in boulder clay, as the

west tunnel was nearing the north shaft; but when the east tunnel got into the sand, it was found desirable to add to the air-compressing plant, and then an additional engine was supplied by the Anderston Foundry Co., Limited, Glasgow. Both engines were used for the east tunnel, the west tunnel being meanwhile deserted. In February 1892, when the air lock for the east tunnel had been completed and the air pressure was ready to be turned on, a 'sand back' discovered itself in the boulder clay, and the water from the river came flowing into the tunnel. This happened on Saturday night when no men were in attendance, but, the air-lock door being closed, only the tunnel was flooded. The difficulty was overcome in twenty-four hours, for with a 15 lb. air pressure the tunnel was blown completely dry. This was the only incident in connection with the boring of the east tunnel, which was completed in November 1892, and the men went into the west tunnel and completed it, as already described, by February 1893.

The centre tunnel only then remained to be driven, and it was completed without a hitch in November 1893, the rate of progress being greater than in the two other tunnels. In one month 30 lineal yards were driven in the middle of the river, and in another month 25 yards. The cost of excavation under pressure, in sand, may be taken to be about 10*s.* per cubic yard, including every operation. The men engaged in the work were well paid, being almost all skilled labourers. The miners got about 8*s.* per diem. The material was run out in bogies, and lifted by a cage from the foot of the shaft similar to those in pits (see fig. 4).

It has already been mentioned, that the passenger tunnel joins the shaft 34 feet from the ground level, and here the lining of the shaft is of wrought-iron segments. At this point the flanges had been turned inwards to the shaft, so that the bolts could be removed and the plates taken off when it came to joining the passenger tunnel with the shafts. The mouths of the other tunnels piercing the brick lining of the south shaft are formed of concrete. On the north side, where there were iron segments at the junction of the vehicular traffic tunnels, special water-tight junctions were made and castings to bolt on to the shaft plates. These special castings were made by the British Hydraulic Company, Whiteinch. The plates of

the north shaft, it may be added, have been caulked with iron rust and sal-ammoniac, so as to make the joints thoroughly watertight.

Over each of the shafts there is constructed a rotunda, with a handsome domed roof giving abundant light. The rotunda is about 80 feet in internal diameter, and 27 feet to the springing level. The dome is supported on steel ribs rising from the springing level and meeting in a curb at the top. There are no tie rods. Over the curb there is a lantern, which is finished outside with a weather vane. The roof is of timber slated, and Pennycook glazing has been largely adopted to give light to the elevators. The rotunda on the north side forms a complete circle except for the entrances to the lifts, but on the south side the outline is broken by the power station, which includes all the motive machinery.

Two sets of pumps have been provided for dealing with the water in the shafts and tunnel. Little difficulty was experienced with water in the south shaft, but in the north shaft more trouble was experienced from this cause, and there is still a considerable flow which has to be dealt with. For this purpose, the shaft is cribbed or lined with iron outside for a height of 30 feet from the bottom. The water is thus allowed to rise for 30 feet behind the lining, passing into a sump in the centre of the shaft. This sump is covered over, and the water from it is drawn off through a 9-inch pipe, passing through one of the tunnels to the south shaft, where it rises 30 feet by its own pressure into a receiving vessel, from which the drainage pumps draw. In the case of the south shaft, the pump works directly from a sump in the bottom shaft. This sump also receives a small amount of service water from the north shaft and from the tunnels.

The pumping machinery is divided into two sets, and the engines are exact duplicates one of the other (see figs. 10, 11, and 12). They are of the bucket-and-plunger type. One set consists of one pump bucket $14\frac{1}{2}$ inches in diameter, with $10\frac{1}{4}$-inch plunger, the stroke being 30 inches; the other $10\frac{1}{4}$ inches in diameter, plunger $7\frac{1}{2}$ inches, stroke 30 inches. The latter is for the smaller duty in the south shaft. The bucket speed is from 80 feet to 100 feet per minute. The south shaft pumps are set

at the bottom of the shaft, the larger pump being placed on a girder connected with the elevator girders, and about 25 feet above the bottom of the shaft.

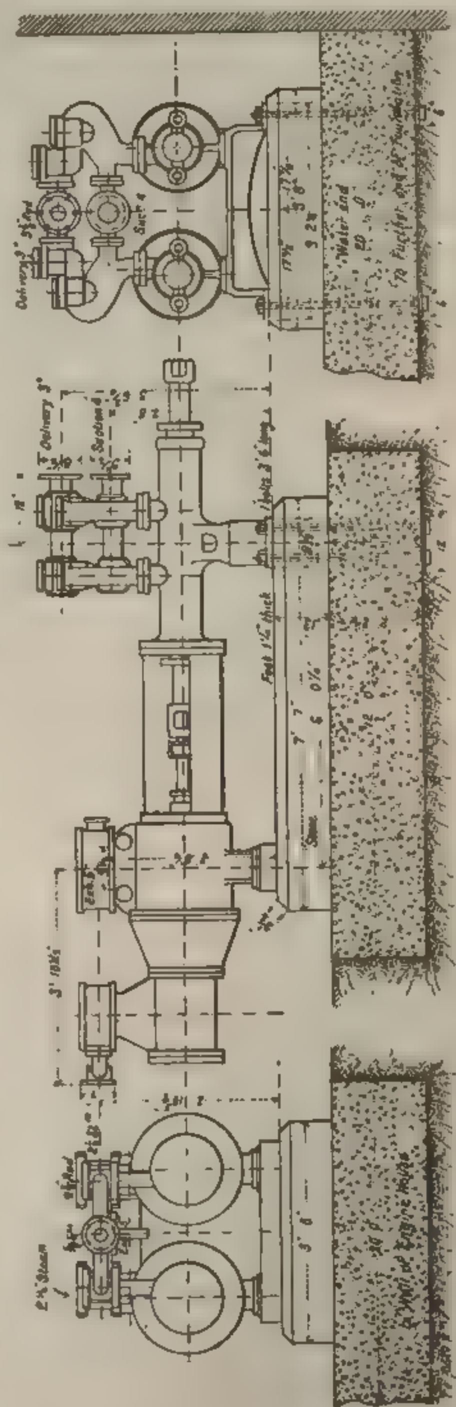


Fig. 12. Fig. 11. Fig. 10

There the suctions are connected with the receiving vessels, already mentioned, by means of sluice valves, so that either pump can be shut off. All the pumps are fitted with liberal air valves and non-return valves, and each set discharges by an independent vertical rising main to a receiving vessel below the pump engines in the power house. The pump valves are all of gun-metal, double-lipped and partially balanced. This system was adopted in preference to the india-rubber or group valve, so that less attention need be given. Each set of pumps is connected, by means of a system of rods and crossheads, of hydraulic tube and cast steel respectively, to a bell crank or quadrant at the top of the shaft, partly in the power house and partly overhanging the shaft. These rods work through slipper guides or sheave guides attached to the sides of the shaft. Each quadrant is driven by a horizontal engine, with steam-jacketed cylinders 9 inches in diameter by 20 inch

stroke, through the intervention of machine-cut geared wheels having a ratio of about 5·6 to 1. The engines are fitted with Korting's ejector condensers, and are arranged for condensing or for exhausting into the atmosphere. The cylinders are fitted with expansion gear, variable by hand, with governors, to come into action only should the speed through any cause become excessive.

Messrs. Crow, Harvey & Co., of Glasgow, constructed these engines to Mr. D. H. Morton's specification and under his supervision. The steam, feed, and exhaust piping is not duplicated, but has been made with special care. The greater portion is of wrought iron lap-welded, with solid welded flanges made by Messrs. A. J. Stewart & Clydesdale, Limited. Numerous sluices and valves are fitted to shut off sections, so as to localise the effect of any breakdown and obviate total stoppage. There are separators for draining the pipes. The donkey-feed pumps are in duplicate.

THE ST. CLAIR RIVER TUNNEL.

Previous to the construction of the St. Clair Tunnel, the greater portion of the heavy traffic of the Grand Trunk Railway between Montreal and Chicago, and between Portland and Chicago, crossed the St. Clair River by ferry. This river runs from Lake Huron to Lake Erie, and forms the boundary between Canada and the United States.

The tunnel was a distinct advance in the construction of tunnels lined with cast iron and constructed by means of a shield. The largest similar tunnel completed up to that time was the City and South London Railway, of an external diameter of 11 feet 3 inches, while that under the St. Clair had an external diameter of 21 feet.

In 1886 the St. Clair Tunnel Company was formed, with Sir Joseph Hickson as president and Mr. L. J. Sargent as vice-president. Mr. Joseph Hobson, chief engineer of the Great Western Division of the Grand Trunk Railway, was appointed as chief engineer of the Company.

Plate XXXI.

Fig. 9.

Fig. 5.

Borings had shown a stratum of soft blue clay throughout the whole course of the tunnel, with pockets of gravel and quicksand and more or less boulders. The greatest depth of water is about 40 feet and the clay is about 50 feet deep; below this is rock. Above the clay lie sand and gravel 5 feet to 25 feet thick with pockets going down into the clay. It was decided to drive the tunnel through the blue clay, and the top of the tunnel at its lowest point is 57 feet below water level.

The site chosen was just below Sarnia and Port Huron, and about three miles below the present ferries. The excavation consists of an open cutting on the American side of 2,500 feet, the tunnel 6,000 feet, and an open cutting on the Canadian side of 3,100 feet or 11,600 feet in all. Of the tunnel 2,290 feet is under the river, 1,994 feet from the river to the cutting on the Canadian side, and 1,716 feet on the American side. The gradients are shown in the longitudinal section on centre line of tunnel, fig. 1, Plate XXXIA, and are 1 in 50 on each side of and 1 in 1,000 under the river.

In 1888 work was begun by sinking shafts on both sides of the river from which to drive the tunnel. After being sunk some distance both were abandoned. The skin friction of the tough clay on the American side prevented the descent of the cylinder, and on the Canadian side the extreme pressure deformed the cylinder and the clay began to rise in the bottom. It was then decided to abandon the shafts and start tunnelling from open cuttings on each side of the river.

In January 1889 the cuttings were begun, and in July and September respectively of the same year the shields were started from the American and Canadian sides. The work was done in open tunnel until the river edge was reached. Here on each side a diaphragm was put in with air locks, and all the work under the river was done in compressed air. The pressure used varied from 10 lb. to 40 lb. per square inch above the atmospheric pressure. To supply the compressed air there was an air-compressing plant on each side of the river, both being supplied by the Ingersoll-Sergeant Rock Drill Company.

The principal difficulties encountered were when pockets of quicksand

and gravel were met and the air blew out in the river bottom. The escape of air was finally sufficiently arrested by plastering the face with clay, and only excavating small portions of the face at a time. Another source of trouble was in the large boulders encountered. These could not be blasted on account of the natural gas in the tunnel, and had to be split by plug and feather.

On August 25, 1890, the two shields met under the river. In just a year 6,000 feet of tunnel had been excavated and lined, and 80,000 cubic yards of material had been removed.

The following table shows the progress each month of tunnel excavated and lined:—

	Canadian End Feet	American End Feet
July 1889	—	53
August	—	114·50
September	73·30	153·70
October	169·45	126·75
November	187·50	225·50
December	217·40	266·91
January 1890	292·35	277·50
February	306·08	273·67
March	292·50	203·63
April	281·34	182·20
May	97·00	355·54
June	236·83	354·46
July	201·30	382·30
August	331·05	314·10

The tunnel is lined throughout with cast iron. This lining is shown in fig. 2, Plate XXXIA. It is 21 feet outside diameter. Each ring is $18\frac{1}{4}$ inches long, measured on the line of the tunnel, and is made up of 13 segments and a key piece. Each segment is 4 feet $11\frac{13}{16}$ inches long on the outside of the curve, $18\frac{1}{4}$ inches wide and 2 inches thick. The flanges are 7 inches deep. The circumferential flanges are $3\frac{1}{4}$ inches thick at the base and $2\frac{1}{8}$ inches at the point. The longitudinal flanges are 3 inches thick at the base, and $1\frac{5}{8}$ inches at the point. The segments are bolted together with $\frac{7}{8}$-inch bolts. On each side of the segment there are twelve bolts, and

on each end four. Each segment weighs about 1,050 lb., and the total weight of the cast iron in the tunnel is about 27,000 tons.

For the radial joints the abutting surfaces of the segments were planed, and between them was placed a packing piece of white oak $\frac{3}{16}$ inch thick. After bolting in place this wood packing absorbed water from the surrounding clay, and in swelling closed the joint perfectly tight. The circumferential joints were made with a layer of tarred canvas. To provide for stopping any leaks which might develop at these joints, the inner edge of these abutting faces was cut away, leaving a groove all round each circumferential joint $\frac{1}{2}$ inch wide and 2 inches deep, which may readily be caulked with lead in case leaks develop. A number of joints where leaks appeared have thus been made absolutely watertight.

Fig. 2 also shows how the completed tunnel is finished off. It is lined with brick and cement to a line a little above the centre line. This is simply to cover the flanges and bolts, and give a smooth interior in case of derailment or other accident; the lining also diminishes the noise experienced from a passing train.

The segments are put in place by an erector fixed to the back of the shield and shown in the perspective view of the shield, fig. 7, and also in figs. 3 and 4, Plate XXXIA. It obtains its circular movement from a shaft on which it is fixed in the centre of the shield. By suitable gearing the segment is swung round to the place it is to occupy, and then thrust out by the bevel gear and screw shown in figs. 3 and 4. Both operations are done by manual power.

The shields were designed by Mr. Hobson and are shown in figs. 5 and 6, Plate XXXIA, and also in the perspective view, fig. 7. They were 21 feet 6 inches outside diameter, and the skin consisted of a 1-inch steel plate. The cylinder was stiffened by five diaphragms dividing it into twelve cells. In front the shield has cutting edges, and at the back it is prolonged 4 feet to cover the lining of the tunnel. As the shield was shoved forward, grout was forced out through holes left in the lining to fill the space left between the lining and the clay.

The excavation was done in the front of the shields, which were then

forced forward by hydraulic jacks, and the erection of the permanent cast-iron lining followed up, the ring being erected inside the tail of the shield. There were twenty-four hydraulic jacks at the back of each shield, each capable of exerting a power of 125 tons, but the greatest total power ever used did not exceed 1,800 tons. These rams are shown in figs. 8, 9, 10 and 11, Plate XXXIA.

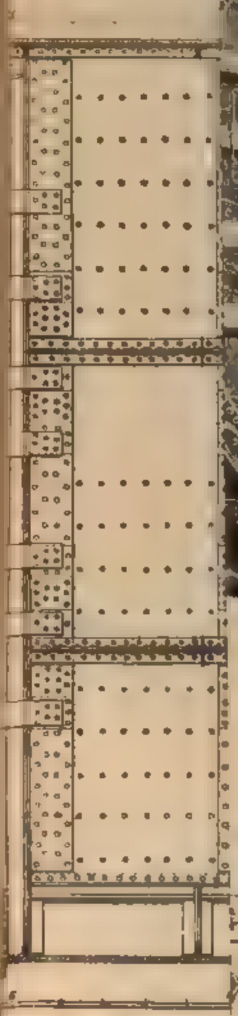
The method of building the tunnel, using the cast-iron lining as the backing from which the shields are forced forward by the rams, necessitated putting the rams as near as possible to the exterior circumference of the tunnel. They were constructed of steel, and a steel collar was placed on the head of the ram to take the entire thrust on one side of the axis of the ram. Each ram could be operated independently of all the others, so as to be able by taking off or putting on rams to correct any deviation in the movement of the shield from the correct line.

The men working in front of the shield cut down the clay, which was carried off in small cars hauled by mules in the compressed air and by horses outside. It was found that horses could not live in the compressed air. The men worked night and day in shifts of eight hours, and although there were three deaths and several cases of partial paralysis, they did not as a rule suffer from any permanent disablement due to the high pressure used.

Mr. Joseph Hobson had a large staff working under him, the principal members of which were, Mr. T. E. Hillman, Mr. M. S. Blacklock, Mr. J. T. Eames and Mr. Thomas Murphy. The rapid and successful completion of this important work reflects the greatest credit on all concerned in its construction.

THE HUDSON TUNNEL.

The tunnel under the Hudson River between New York and Jersey City is one of those works which has been dogged by bad luck ever since its commencement. Begun in 1874, it still remains unfinished. A large book might easily be devoted to a full account of the work which has been done



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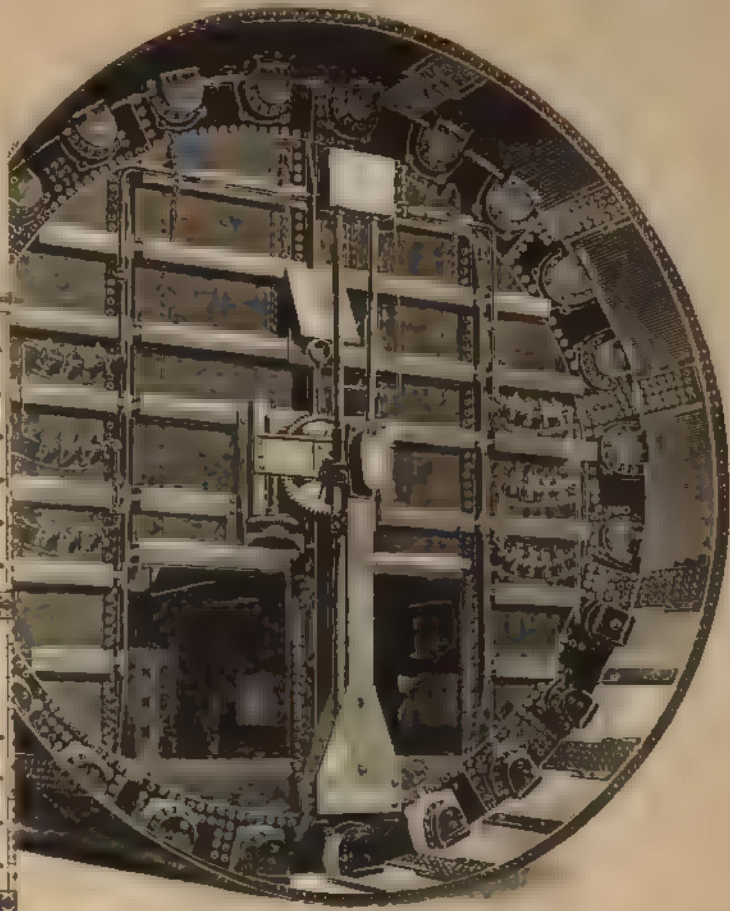


Fig. 7.

Fig. 8.

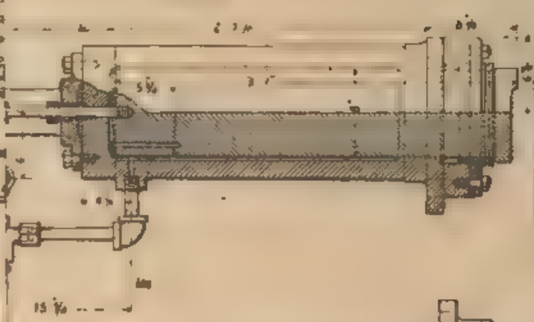
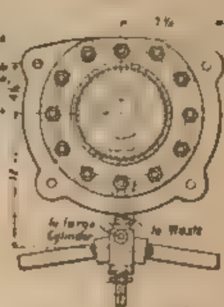


Fig. 9.



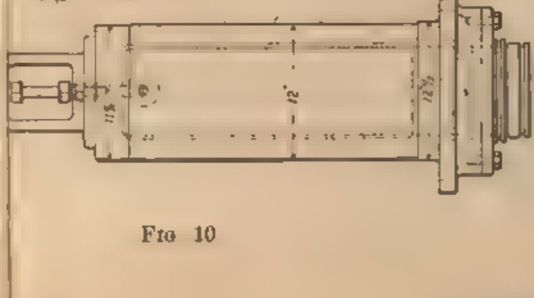


Fig 10

Fig. 11.

[*Between pages 494 d and 494 e.*

from time to time on this difficult undertaking, but on the present occasion space prevents us from doing more than glancing quickly at the leading features.

The construction of the tunnel was undertaken to afford direct railway communication between New York and the many railroads which now have their termini in Jersey City, thus taking to a certain extent the place of the ferries which are the only means of communication at present. The many delays due to fog, ice, and other causes, which occur in ferry transportation, make this means of communication unsatisfactory and uncertain.

Fig. 1, Plate XXXIB, is a cross section of the river showing the position of the tunnel. The width of the river is about 1 mile, and the depth of water in the channel about 60 feet. It had been ascertained by borings that with the exception of a little rock on the New York side the construction would be altogether through silt.

Mr. D. C. Haskin was the President of the Company which was formed to undertake the work. The Consulting Engineer was Col. W. H. Paine; the engineers in charge were Messrs. Spielman and Brush, and the Superintendent was Mr. J. F. Andersen.

The sinking of a shaft from which to start the tunnel was commenced on the New Jersey side in November 1874, but after it had been sunk to a depth of 14 feet below H.W. work was stopped for some years owing to legal difficulties, and it was not until 1879 that it was sunk to its full depth. This shaft was 30 feet in diameter inside, and was sunk to a depth of about 60 feet below H.W. level. The work of excavation from the side of the shaft was then commenced under compressed air, and a temporary chamber was formed outside the shaft large enough to start two tunnels from. The north tunnel was first commenced.

The method adopted was to take out the excavation in terraces. In the meantime the lining of the complete section with $\frac{1}{4}$-inch thick iron plates was carried on. The silt was removed until the top centre plate of a new ring of this lining could be put in and bolted to the one behind. Then a plate was put in at each side and bolted to the centre plate and to the last ring. When this circle had been carried down the sides some distance another was com-

menced and built in the same way. These plates were propped to a small extent either from the invert of the completed tunnel at back or from foot-blocks on the silt. When four complete rings of plates had been put in, the chamber was cleaned out and the brickwork laid, thus completing a length of 10 feet. The plates were of $\frac{1}{4}$-inch wrought iron, 2 feet 6 inches wide and 6 feet long, and were flanged on the four sides. Narrower plates were used sometimes when the ground was very bad. It will be noticed that Mr. Haskin relied almost wholly upon compressed air as a means of temporarily upholding the ground until the brickwork of the tunnel could be put in. A good deal of difficulty was experienced in preventing the crown and sides from coming in, and in overcoming the tendency of the whole section to deformation. The tunnel was 16 feet wide and 18 feet high inside the brickwork.

By the middle of 1880 the north tunnel had been advanced some distance under the river, and the south tunnel had been commenced. At this stage it was determined to complete the temporary chamber outside the shaft referred to before, and to make at this point a permanent brickwork chamber common to both tunnels; but while this was being carried out the chamber collapsed, and twenty men who were working in the tunnel lost their lives.

By means of a new caisson sunk from the surface on to the temporary chamber the work was again reached, and a permanent brick chamber was built at this place.

Shortly after recommencing work the 'pilot' system, the invention of Mr. J. F. Anderson, the superintendent, was adopted, and the thickness of the brick lining was increased to 30 inches. The 'pilot' system consists primarily of an iron tube about 6 feet in diameter advanced by the poling process in the centre of and in front of the full-sized section of the tunnel. The pilot is in fact a small iron tunnel built up piece by piece as the excavation in front is made, and taken down piece by piece at the back as the tunnel is completed, the last plates taken down at the back going to form the next section of the pilot in front. The plates are of course only bolted together. This tube is therefore supported at one end in undisturbed material,

and the other end is supported in the completed portion of the tunnel. The full section of the tunnel is then excavated and lined with thin iron plates as before described, these plates being strutted to the pilot tube as they are put in. Hence short small timbers are only required for strutting purposes.

As the work advanced bulkheads with air locks in them were built in the tunnel at intervals of about 400 feet, so that only the portion of the tunnel next to the working face was kept under the full air pressure of 30 to 35 lb., the next section being at a pressure of 20 to 25 lb. and the remainder of the completed portion being under the normal atmospheric pressure.

By the methods above described the north tunnel from the New Jersey side was completed for nearly 2,000 feet, and the south tunnel for a short distance. On the New York side a timber caisson had been sunk, and the north tunnel had been started from it.

When the undertaking had reached this stage, in November 1882, the work was stopped for want of money.

After the lapse of six years the scheme was again revived with English capital. Sir John Fowler, Sir Benjamin Baker, and Mr. J. H. Greathead were appointed consulting engineers, and Mr. W. R. Hutton was chief engineer in New York. The contract for the work was taken by Messrs. S. Pearson & Son, of Westminster, and Mr. E. W. Moir was appointed as their engineer and agent in New York.

It was decided that the portion of the tunnel still remaining to be done should be formed with a cast-iron lining of sufficient strength to take up the whole pressure of the ground, and that a shield should be used to facilitate the construction. The work was again started early in 1889.

The first operation was to construct the shield at the end of the already completed portion of the tunnel. This was a most difficult operation, as a chamber had first to be formed in which to construct it, the material for the shield had to be brought down piecemeal, and the riveting of it together had to be done under an air pressure of 35 lb. above the atmospheric pressure.

The shield is shown in figs. 2, 3 and 4, Plate XXXIB. It is 10 feet 6 inches long from the cutting edge to the back, and the outside diameter is 19 feet 11 inches. The outer skin is made up of two $\frac{5}{8}$-inch steel plates with internal covers and packing pieces between the covers. A vertical plate-iron diaphragm is fixed at right angles to the axis of the shield at a distance of 5 feet 8 inches from the cutting edge, dividing the shield into two parts. The portion of the shield at the back of this diaphragm, commonly known as the tail of the shield, consists only of the outer skin above referred to, but forward of the diaphragm there is also an inner skin of $\frac{1}{2}$-inch iron plates separated from the outer skin by a distance of 17 inches, and attached to it by longitudinal and circular diaphragms, and both skins come together near the cutting edge. The forward part of the shield is divided up by two vertical stiffening diaphragms in the line of its axis and also by two horizontal diaphragms. The face of the shield is therefore divided into nine compartments, and there is access to each compartment from the back by small doors in the cross diaphragm.

The rear part of the shield is without divisions, and in this the cast-iron tunnel segments are erected.

The whole structure is shoved forward by sixteen hydraulic rams fixed to the back of the shield and butting against the last ring of cast iron erected. The ram cylinders are fixed between the inner and outer skins in the forward part of the shield.

If a ring is erected in the tail the rams butting against this ring shove the shield forward far enough to allow space for the next ring to be erected between the last ring and the rams, when the latter are drawn back into their cylinders. The tail of the shield, however, still laps over part of the last ring, so that at no time is any portion of the ground exposed at the back of the shield. The new ring is then erected and the same process repeated.

The outside diameter of the cast-iron rings is 19 feet 6 inches. Each ring is made up of eleven segments and a key piece. The thickness of metal is $1\frac{1}{4}$ inches, and the depth of flange 9 inches. The circumferential joints are made iron to iron with the exception of a small recess left in the

inner face for caulking, and are not machined; the longitudinal joints had a wide planed fillet all round the face of the joint. The length of each ring was 1 foot $8\frac{1}{4}$ inches. A ring is shown in figs. 5 and 6, Plate XXXIB.

To erect the rings Mr. Moir designed an hydraulic erector carried on a carriage travelling on rails laid on brackets attached to the cast-iron lining already in place. This is shown in fig. 7, Plate XXXIB.

As already stated, the tunnel was driven through soft silt, and a great deal of difficulty was at first experienced in driving the shield at the right level on account of the tendency of the cutting edge to dip down in such soft material. With a little practice, however, it was found possible to drive it at such an inclination as to make allowance for its coming down to almost the exact right level.

It was not necessary to excavate the material in front of the shield by hand, as on account of its semi-fluid nature it squeezed through the doors at the back of the shield as the latter was shoved forward by the hydraulic rams. Fig. 8, Plate XXXIB, is a skeleton longitudinal section of the tunnel showing the method of working.

There was a good deal of illness and several deaths among the men working in the high-air pressure of 35 lb. above the atmospheric pressure. In the majority of such cases intense pain in the limbs is felt, which is generally relieved by returning into the compressed air. The contractors made therefore what was practically a small air-tight iron hospital on the ground level, in which any desired pressure of air could be obtained from the air-compressing engines. Those who were suffering were put into this hospital, and the pressure raised sufficiently to remove the pain, and then by letting the pressure fall very gradually they were in many cases able to return to the atmospheric pressure without recurrence of pain. Of course this is only *one* of the methods adopted for the treatment of illness due to compressed air, but the whole subject of compressed air illness is too large to touch on here.

Messrs. Pearson & Son completed about 1,900 feet of the north tunnel by July 1891 (the best progress in any one week being 72 feet), and at this time the work had to be stopped again for want of money, and has not

been resumed up to the present time (April 1896). Fig. 1, Plate XXXIB, shows the amount of work done on the north tunnel, and no work has been done on the south one since 1881.

It will be understood that the tunnel under the Hudson is of course only the connecting link between the numerous railway extensions intended to be constructed on either side of the river on its completion. The whole scheme includes large terminal and other works both in New York and Jersey City.

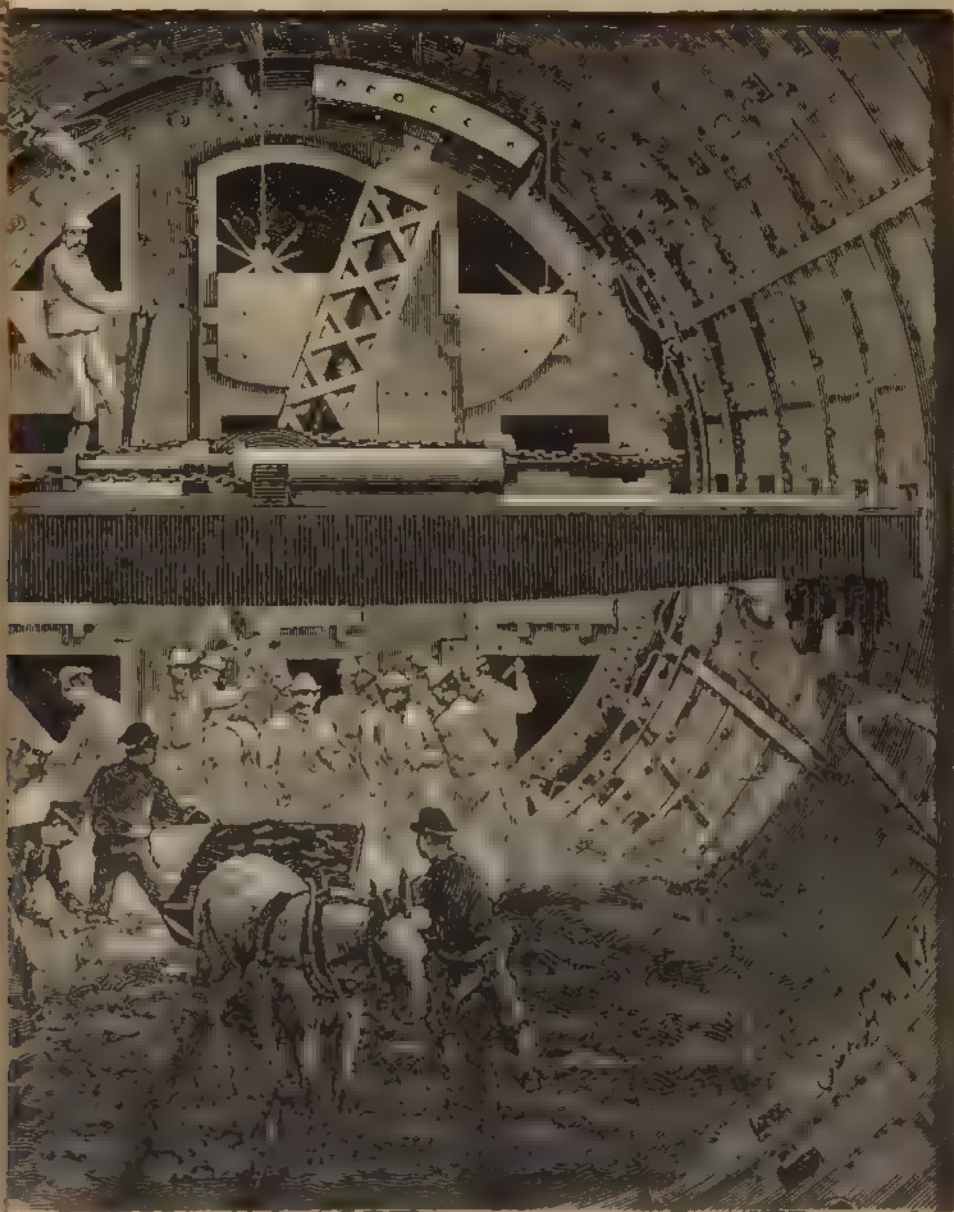


FIG. 7

Between pages 494 and 495

CHAPTER XXXV.

TUNNELS THROUGH CLAY, GRAVEL, ETC.

THE NEW KING'S CROSS TUNNEL LONDON.

THE construction of this tunnel was commenced in 1890. It was necessitated by the increased traffic into and out of the Great Northern Company's terminus; and to relieve the occasional congestion thus caused, a third double line of railway was decided upon to receive the local traffic, and thus relieve the main line traffic. To accomplish this a tunnel 530 yards long was requisite. The tunnel is principally remarkable as being the means of introducing to notice an entirely new but simple method of driving, the patent of Messrs. Jennings & Stannard, of Westminster, and the result may be considered to have been entirely satisfactory.

In its course the tunnel passes under the Regent's Canal. It is of three different sections, varying according to the headway, which was at times exceedingly shallow. Where sufficient headway permitted, the section is oval, the invert being somewhat flat; the height is 25 feet 3 inches, and the greater diameter 26 feet. Another section is circular, the height being 22 feet 3 inches and the width 26 feet as before. The length of the tunnel when passing under the canal on the skew is 165 feet; the roofing is of cast-iron, cross, hog-backed beams 31 feet span, 2 feet deep at centres, and 3 feet wide.

The tunnel is built of eight rings of brickwork 3 feet thick throughout, the two inner rings being of blue bricks and the remaining six of ordinary red brick. The rail level is 4 feet 9 inches from the invert, through the centre of which runs an arched sewer. Manholes are built at a distance

of 50 feet on each side of the tunnel, the spaces on alternate sides being thus 25 feet. Two shafts have been opened, the headings being driven in each case north and south from both, and another heading driven at either end. The excavation being principally through hard blue clay, the work progressed rapidly.

By the new system of driving the tunnels, the ordinary timber bars are superseded by a series of iron or steel bars or needles, which are grooved longitudinally so that they may be linked together, but sufficient play being allowed to permit of the bars being arched without difficulty, whilst at the same time longitudinal motion only is allowed. The needles when joined together form a temporary roofing, and when the work is commenced they can be supported on timbers at either end whilst the building of the brick archway is proceeding. The needles used at the King's Cross Tunnel are 10 feet long by 6 inches wide and 2 inches deep. When the brickwork is built underneath the needles, they are pushed forward either singly or three at a time. At intervals along each needle are holes into which a boss or bracket may be fixed, and a screwjack, which has the completed portions of the brickwork for an abutment, is turned, presses against the bracket, and drives the needles forward. The needles have cutting edges, and thus shape the excavation to the desired sections. The needles being driven forward until only a few feet rest on the completed brickwork, the other end is timbered up, and the raking struts support the needles and the sides and roof of the excavation whilst the horizontal bars support the face. The needles are provided with longitudinal tubular cavities, through which cement grouting is driven in tubes when the needles are pressed forward. This fills up the space above the brickwork previously occupied by the needles, and thus prevents any subsidence of the surrounding soil.

The great advantage derived from the use of these needles is the ability of being able to continue work with limited headway without the necessity of adopting the cut-and-cover system, the space occupied by the needles being only some 2 inches in place of the 24 inches usually occupied by the ordinary timberings. They were, therefore, especially useful in

the work in question, which passes under the Great Northern goods station and Metropolitan Cattle Market at a distance of only some 6 feet below the ground level.

THE WEST CHICAGO STREET RAILROAD TUNNEL, U.S.A.

This tunnel has been constructed by the West Chicago Street Railroad Tunnel Company, and is intended exclusively for double track cable traction. The line of the tunnel is located upon private property, situated nearly in the centre of the business district, and passes under several large buildings, the Chicago River, and also under the yards and trucks of several railway companies at the southern entrance to the Union Depôt, which is the largest and most important passenger station in the city.

The tunnel and approaches, extending from the east line of Clinton Street to the west line of Franklin Street, will be 1,514 feet long, the tunnel proper being 920 feet long, with gradients ranging from 5·46 per cent. to 10 per cent., as shown on the profile (fig. 1, Plate XXXII.).

The general design of the work is shown in the appended illustrations (figs. 2 to 8, Plate XXXII.), the tunnel being a three-centred arch, and having a clear span of 30 feet and a clear height of 15 feet 9 inches above top of rail. The masonry is of brick, seven rings or 32 inches in thickness, excepting a short length under the railway tracks, where the thickness is increased. Two outer rings of masonry in the tunnel are laid in asphalt mortar, composed of Trinidad asphalt and gypsum, which mortar has been found to be a perfect protection against leakage of water and dampness in tunnels. All other parts of the masonry are laid in hydraulic cement mortar.

The invert arch, the backing and filling over the haunches and crown, are of Portland cement concrete (fig. 2). All spaces between the masonry and sheeting, and all irregularities, are filled in solid with concrete. Suitable provision for drains and appurtenances have been made, to take care of all

water which will unavoidably enter the tunnel down the approaches during rains and heavy storms.

The river section of the tunnel was built in a coffer dam, one half at a time, the navigation of the stream making an unobstructed channel at all times necessary. The land sections are constructed in open trenches. The soil cut through is chiefly a heavy, semi-fluid clay, which, together with the surcharge of lofty buildings, and the vibration due to the railway traffic, renders the use of a very heavy type of timbering necessary. Not the least important and difficult part of this work has been the supporting and maintenance of the various railway tracks crossing the excavation, without interfering with the interlocking system or obstructing the running of trains. This portion of the work has been successfully accomplished by the introduction of temporary switches, and by supporting the tracks on substantial pile bridges before the excavation was commenced. The average width of the trench is 40 feet, and the greatest depth excavated 52 feet.

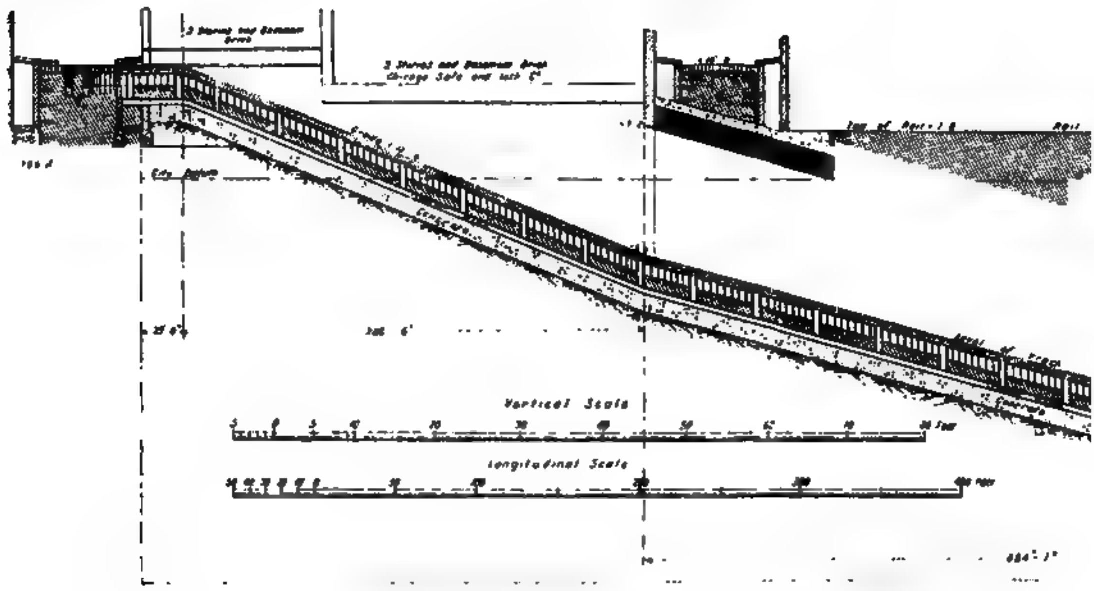
Work was commenced in February 1890, and it was anticipated that the cost would exceed one million dollars.

PARIS UNDERGROUND RAILWAY.

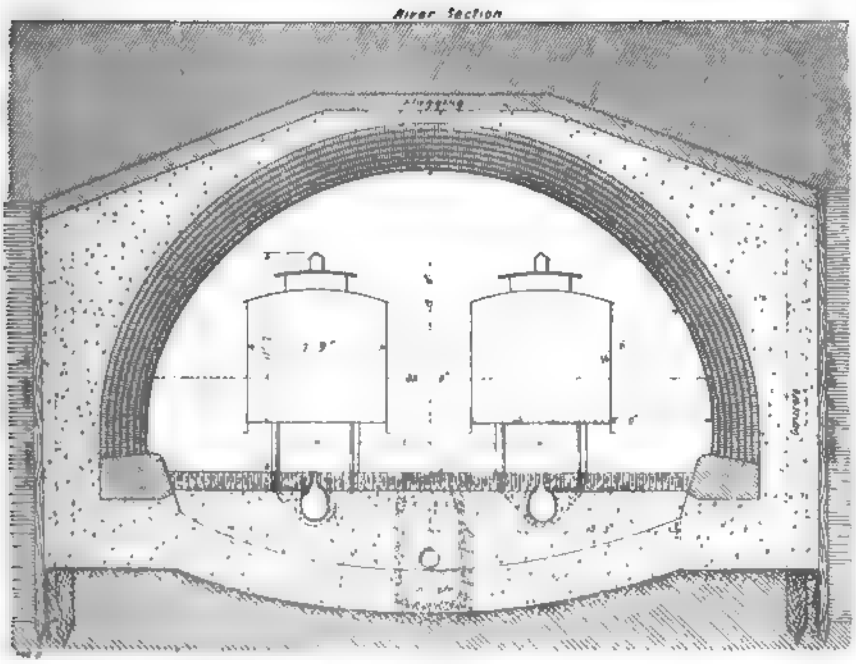
The question of increased railway facilities in Paris has been before the municipal authorities for some years past, and, at last, the commencement of an underground railway is on the point of becoming an accomplished fact. Many serious difficulties will present themselves in the course of the work, which may be regarded as the precursor of the Metropolitan Railway of Paris, which, it is hoped, will be well advanced towards completion in time for the Great Exhibition to be held in 1900.

The construction of the new line, which will necessarily be below street level, will present numerous difficulties, the greater portion being in tunnel or covered way. It was impossible, of course, to adopt an even approximately straight course, because of interfering with buildings, and passing under streets. The portion passing under the Rue Denfert and

West

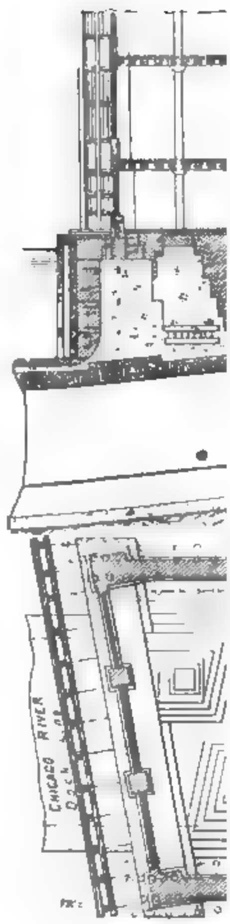


Vertical Scale
Longitudinal Scale



River Section

Fig. 2.



CHICAGO RIVER

Boulevard St. Michel, especially presented serious difficulties. The Muni-

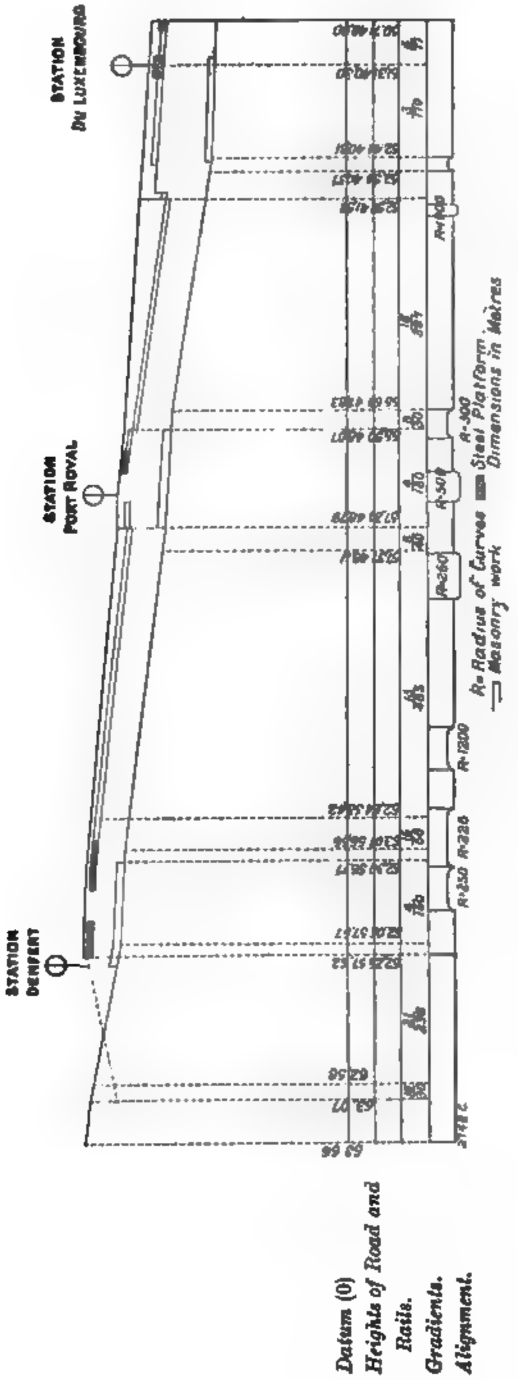


FIG. 1.—DIAGRAM ILLUSTRATING PROFILE OF THE PARIS UNDERGROUND RAILWAY.

cipal Council of Paris is, for many reasons, opposed to a metropolitan

railway; and they did not fail to impose various conditions, on the ground of saving the public from inconvenience during the progress of the work. Besides this, one of the most important tramways in Paris runs along the two thoroughfares above named. This tramway, which extends from the Gare de l'Est to the fortifications south of the Gare Denfert, could not be interfered with during the process of construction. The Rue Denfert is very narrow, and some means had to be devised by which the railway could be constructed without interfering with the public traffic. The ordinary way of driving tunnels was out of the question, on account of the nature of the ground; and a network of mains and sewers added to the difficulty. In addition to this, the whole of this portion of Paris overlies a vast system of catacombs, the arched roofs of which are apt to fall in at very slight provocation. As will be seen on reference to the illustration (fig. 1 on page 499), which gives the profile of the line and the level of the streets under which it passes, the surface, after rising for a short time, descends again very rapidly towards the Seine; this condition involves the adoption of somewhat severe gradients to keep it sufficiently beneath the surface of the ground. The close and unavoidable approach of the line to the Observatoire rendered the authorities of that institution naturally apprehensive that the vibration of passing trains would interfere with delicate operations, and special precautions had to be taken to avoid this. By reference to the profile, it will be seen, that the platforms of the stations and the archway of the tunnel are shown by a double line when made in masonry, and by a sectional tint when ironwork is adopted.

It was necessary to start with a 1·6 per cent. grade, increased after about 300 yards, to one of 2·1 per cent. In this way the line reaches the new Denfert station. Fortunately, at its commencement the railway passes under a large open square, so that no buildings were interfered with, and the work was carried on in open cutting, afterwards closed by covered way, except for a length of about 170 feet, which was kept clear for ventilation. One end of the covered way forms part of the station. The type of structure adopted is very similar to that used in some of the covered ways of the Metropolitan Railway in London. It consists of two longi-

tudinal beams resting on iron columns of I section; the longitudinals are connected by transverse girders 29 feet 6 inches in length, and bear at the ends on the side of the retaining walls. Brick arches are turned between the transverse girders forming the roof of the covered way and carrying the street above. Beyond the station, the level of the rails is not low enough to permit of anything but covered way, of the type shown in fig. 2; this is carried on for about 280 feet, and in this length is included a curve of 738 feet radius, rendered necessary to bring the line towards the Rue Denfert. Various gradients extend for some 1,800 feet, the rail level consequently varying from 15 feet to 27 feet 7 inches below the surface.

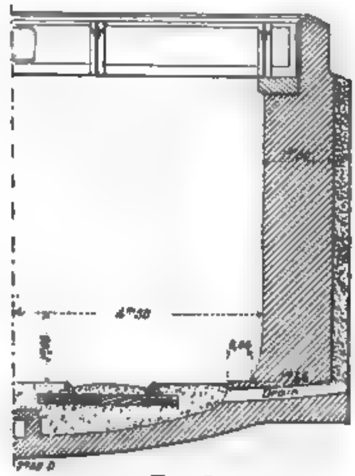


FIG. 2.

This section terminates with the Port Royal station, located, like the preceding one, in a large 'place,' an open space, rendering it possible to construct the station in open cutting. The line beyond is in open cutting for a distance of 286 feet, and beyond this is a length of ordinary tunnel of the type shown in fig. 3. This section is continued under the Boulevard St. Michel, where the gradients are almost uniform, the ruling incline being 1·6 per cent. These grades are continued to the end of the line, where the rails are 36 feet below the surface. There was no absolute necessity for adopting such a depth, but it was considered probable that in the future it would be desirable to connect with the contemplated metropolitan system, and that in that case such a level would be found a convenient one.

In the illustration of the profile of the line (fig. 1) is shown the position of the Luxembourg Station, where the form of construction is altered to that shown in the annexed section (fig. 4). The tunnel is extended beyond the station, the space being utilised for engine sheds, &c. To make the line nearly horizontal at this point, the formation has been made up with ballast to compensate for the fall in the tunnel. If

the line is extended hereafter towards the interior of Paris, this ballast will be taken away.

The drain, gas, and water pipes which were encountered in the subsoil, though numerous, were fortunately only small, and although the work of excavating was tedious, it did not present many serious difficulties. But consolidating the ground over the old quarries or catacombs was a more difficult matter. The roofs of these excavations lie from 39 feet to 72 feet under the rails, but their existence has long been a source of danger to the foundations of the houses, which occasionally give way. These excavations have, in places, been made in two storeys, thus increasing the danger. Where the roofs of the quarries had not fallen in, a wall was built from the floor to the top, under the right side wall of the tunnel; when, on the contrary, the roof had broken down, the process shown in fig. 5 was adopted. A well was sunk to the floor of the quarry and lined with heavy masonry, the top being arched, so that the tunnel was firmly supported. About 20,000*l.* was expended in this work alone. The precaution was adopted of introducing a thick backing of sand between the wall of the tunnel and the gardens of the Observatoire. But that the directors of this institution were unnecessarily alarmed by the possible effect of the vibration caused by passing trains on the delicate instruments, was demonstrated by the fact that at the time the directors were protesting, heavy ballast trains were passing through the unfinished tunnels without the knowledge of the officers of the Observatoire or detriment to the instruments.

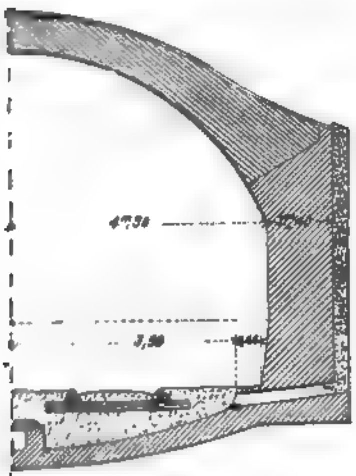


FIG. 8.

It was necessary to carry on the construction of the tunnel in such a way as to inconvenience the public as little as possible, and, at the same time, to push the work on as quickly as possible without incurring undue expense. The plan adopted was as follows. The two lines of tramways running from Montrouge to the Gare de l'Est were shifted to the side-

walks, whilst ordinary vehicles were allowed to circulate on the Rue Denfert and the Boulevard St. Michel, except in those places where there were parallel streets available. The system of construction adopted left one side of the street undisturbed, and rendered the building of the tunnel without centreing comparatively easy. A trench (or, where more convenient, a series of pits) was excavated, and on these the piers were erected for a certain length. The street surface was then lowered to the width of half the tunnel, and to a level and form corresponding to the contour of the arch. This contour was covered with a bed of plaster, and this served as a foundation on which to lay the masonry of half the arch.

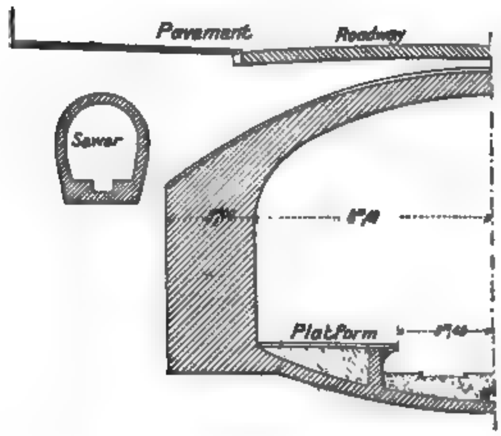


Fig. 4.

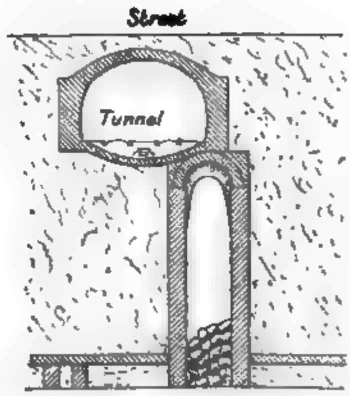


Fig. 5.

After the work was completed in this manner, and the street level restored, a similar method was followed on the other side, and the lengths of covered way were put in in the same manner. As soon as the work was completed as described, the excavation was carried forward without any interruption to the traffic, and the invert, drains, &c. were put in. Such a method of construction would, of course, only be followed under the difficult conditions imposed by the necessity of not interfering with the traffic, but, though somewhat slow, the result was in every way satisfactory.

The three different types of construction occur in this work in the

following proportion: masonry tunnel, 79·7 per cent.; iron and brick covered way, 15·2 per cent.; and open cutting, 5·1 per cent. The tunnel, of which a section has already been given in fig. 3, is made with a segmental arch, 15 feet 9 inches in radius; it is entirely of dressed stone set in Portland cement, and is covered at the back with a coating of cement and a second one in asphalt. The invert is also in masonry set with hydraulic lime mortar; the curve of the upper side has a radius of 41 feet. The height of the vertical side wall is 9 feet 5 inches, and the width 45 inches, including the voids filled with loose stones for drainage channels. The width of the tunnel is 29 feet 6 inches. It may be added, that along the side walls refuges are formed for the use of the tracksmen, at intervals of about 50 feet, and a narrow walk is left at the foot of the walls 17 inches wide. Similar arrangements are made in the girder-covered way (fig. 2). Here the clear headway is 15 feet 9 inches to the under side of the girders; in the tunnel section it is 19 feet 8 inches, and the side walls are somewhat thicker.

On a line constructed chiefly in tunnel, and especially at a station like Luxembourg, which is mainly underground, adequate ventilation is a matter of great importance. Provision for this is made by the construction at intervals of downcast shafts that convey air into the tunnels, either through openings in the side walls or at the top of the arch. There is, in addition, a channel running through the tunnel, and connected to a powerful fan, installed in the basement of the Luxembourg station, in the house under which this station has been constructed. This fan drives the vitiated air into a chimney constructed close to the station. The ventilator is to be driven by electricity, and the current is to be brought from a power installation which has been erected near the Denfert station. It will contain dynamos for lighting the stations and lines, operating elevators, &c.

The estimate of cost of construction was 348,000*l*., and although it is not possible at present to give what has been the actual expenditure on this interesting work, it may safely be assumed to have been far heavier than the estimate. The sum of 58,000*l*. has been expended solely in the purchase of the house utilised for the Luxembourg station.

The construction of this underground railway is referred to in a report by Mr. W. M. Barclay Parsons, addressed to the Board of Rapid Transit Commissioners of New York, and entitled 'Rapid Transit in Great Cities.' The work is characterised as the most important piece of underground construction in Europe, and the only one in which any attempt has been made to produce a really handsome structure. Although this commendation is no doubt fully justified, the fact must not be lost sight of that the length is only 6,240 feet. Mr. Parsons also refers to the remarkable rate of progress made with the tunnel under the difficult conditions, already referred to, of maintaining the street traffic and removing the core only after the masonry was finished. Some conclusions arrived at by the French engineers who were engaged on the work, and based on the experience they obtained, are appended. They are:

(1) To use masonry in preference to iron.

(2) To avoid specially dimensioned stones in the masonry.

(3) To remove and introduce all materials by train in preference to conveying them through the streets in wagons.

(4) To use simple materials in constructing, especially concrete.

(5) To keep the rail level as close to the surface as possible, as the expenses and difficulties are found to increase with the depth.

It should be mentioned, that the material dealt with was principally sand; it is stated that the most profitable part of the work to the contractors was the removal of the core at the rate of 2*s*. 3*d*. per cubic yard.

The contract prices were as follows:

	£	s.	d.	
Excavation removed by carts, with haul of 3 miles	0	3	10	per cubic yard
" piled on one side and used as back filling	0	1	7	"
" removed by railway, with haul of 3¾ miles	0	2	3	"
Masonry, rubble in lime	0	16	10	"
" " cement	1	0	10	"
" cut stone, soft	1	16	11	"
" " hard	2	7	8	"
" exposed voussoirs	4	2	8	"
Brickwork (not exposed), in lime	1	8	10	"
" (exposed), in cement	1	14	4	"
Iron, wrought, in girders	17	5	0	per ton
" cast "	12	12	0	"

THE CITY AND SOUTH LONDON RAILWAY.

By the original scheme, this undertaking was designed to provide an easy and rapid means of communication between a terminal station near the Monument, in the City, and the large district traversed by the road running south-west by south from London Bridge to Stockwell, passing *en route* through the Borough, Newington Causeway, Elephant and Castle, Kennington Park Road, and Clapham Road. The line, which was at first designated a subway, lies underground throughout its entire course. It was commenced in 1886 and completed in December 1890, electricity being ultimately adopted as the means of traction. Mr. J. H. Greathead was Chief Engineer, and Sir John Fowler and Sir Benjamin Baker were Consulting Engineers.

The line has been laid practically without any interference with existing structures; and throughout its whole route there is only one spot where private property has been trenched upon. The economy, however, which has been obtained in keeping the subway at a low level has entailed the disadvantage of having the stations at considerable depth below the streets, the actual distance varying from 40 feet to 60 feet. This drawback the company have endeavoured to counteract by the introduction of suspended hydraulic hoists. A lift well 25 feet in diameter, lined with iron rings, has been constructed at each station, in which two cages work, each holding fifty people. The success or failure of the undertaking will doubtless considerably depend upon the care and skill with which these elevators are worked.

The total length of the way from the City to the Swan at Stockwell is $3\frac{1}{6}$ miles. The up-and-down lines are absolutely distinct, each being carried in an iron tunnel, which has been built in segments bolted together. These two tunnels do not in all cases run side by side, and, as a fact, the down line, before it reaches Swan Lane, has taken up a position 5 feet below that containing the up line. This arrangement has been adopted, because the lane is too narrow to permit of the two tunnels being

run on the same level without encroaching on the rights of private property.

At the bottom of Swan Lane the two tunnels enter the river bed, the upper one being 15 feet below the surface. When the opposite river bank is reached, there is no convenient roadway for the subway to follow, and it has, therefore, been taken underneath Hibernia Wharf into Borough High Street. After this point has been reached, the two tunnels maintain their relative positions, being situated, in plan, side by side, with about five feet intervening; but in section one of them is at a lower level than the other, in order to render it possible to work the traffic at the intermediate stations entirely from one side, thus reducing the standing expenses at the station. At the termini the lines converge into one tunnel in order that the trains may pass from one line to the other. Each of the tunnels has an internal diameter of 10 feet 6 inches. It is formed of rings in segments bolted together by internal flanges. Each ring is 1 foot 7 inches long, and is composed of six segments of equal size and a short key segment with parallel ends. The flanges are $3\frac{1}{2}$ inches deep by $1\frac{1}{4}$ inches thick, and are secured together by $\frac{3}{4}$-inch bolts. The circumferential joints are made with a tarred rope between a 'chipping edge' and the bolts, and the longitudinal joints with pine strips, and all joints are pointed with Medina cement.

The method of construction which Mr. Greathead adopted is as simple as the tunnel itself, and when in progress was thus described: At the head of the subway, assuming that a short length of tunnel is already in place in the clay forming the river bed, there is a steel shield consisting of a cylinder 6 feet long, and of sufficient diameter to slide easily over the portion of the subway already bolted together. The forward end of this cylinder has a cutting edge, whilst about midway of its length there is a bulk head, having a door in it. Through this aperture the workmen remove a part of the clay in front, cutting out a small chamber considerably less in diameter than the shield. When this has been done, the shield is forced forward by 6 hydraulic rams fed by two hand pumps. The hydraulic cylinders are bolted to the shield, whilst the ram heads abut against the last completed ring of the tunnel. The cutting edge clears

out an exact circle in the clay, forcing the material into the space prepared for its reception, from which it is dug out and loaded, through the door, into skips for removal. As the shield moves forward it leaves in its rear an annular space of about one inch between the iron and the surrounding clay, and this is immediately filled with grouting to prevent any subsidence either of the tunnel or of the ground. The grouting is made of blue lias lime and water, and is mixed in a wrought-iron vessel provided with paddles, which can be worked from the outside. The vessel is closed, and air, at a pressure of 30 lb. to 40 lb. per square inch, is admitted to it whilst the paddles are at work. By means of a hose pipe ending with a nozzle, the grouting is forced through holes left in the iron lining into the space between it and the clay, until the entire cavity is filled with a shell of cement. This forms an impenetrable coat round the subway, and protects it from moisture and oxidation. When the shield has been moved forward, a ring of segments is bolted on, the rate of progress being about 10 feet in the 24 hours.

By permission of the Thames Conservators, a staging was erected in the river behind the Old Swan Pier, and from this a shaft was sunk through the river bed to the depth of 82 feet below high-water mark. The skips of clay are, when filled, lifted from the bottom of the shaft by means of a crane and placed on a tramway, along which they run to deliver the contents into barges. The shaft is 13 feet diameter, and is made of cast-iron rings cast in one piece $1\frac{1}{8}$ inches thick. The shaft was made in the usual manner by removing the material from the inside by means of a grab. It was found to be of great use subsequently in constructing the tunnels and station in the City, as through it were conveyed all excavated materials, iron, bricks, &c., not only in that direction, but also southwards for a distance of more than half a mile. From its position in the Thames this shaft offered no obstruction to the navigation, and all the land shafts being upon the private property of the company, practically no hindrance was caused anywhere to the traffic.

Frequent borings, generally 3 inches in diameter, were made from the surface along the course of the railway, sufficiently far in advance of the

work in progress to allow of arrangements being made to meet the conditions which were thus ascertained to exist. These borings disclosed that the tunnels throughout their whole length were either under or in water-bearing strata, which were, to a greater or less extent, in communication with the river, and were penetrated by water at intervals of time corresponding with the tidal movements of the river.

It had been the original intention to work the traffic by an endless cable, and the gradients and curves were, therefore, steeper and sharper than would have been constructed for a line to be worked by locomotive engines. The curves, however, could not have been reduced without altogether altering the route, which might have involved serious opposition or heavy expense, or both, for right of way under buildings.

As no locomotives are used in the subway, the greatest cause of foul air—viz. sulphurous acid—is absent, and the ventilation of the tunnels has presented but little difficulty. The ventilation is, moreover, facilitated by the direction of the traffic through each tunnel being constant; the trains being, in consequence, a series of pistons which tend to maintain an active circulation of the air. The benefit in the direction of ventilation, which might be obtained by the passage of trains in ordinary tunnels, is to a large extent neutralised by the services of the up and down lines running in opposite directions.

The permanent drainage of the tunnels is effected by means of small injector hydrants, which are placed in the inverts at every depression in the line, and are connected to the hydraulic main supplying the lifts, and to a 2-inch pipe carried along the tunnel to, and up, the nearest shaft. These injectors cannot easily get out of order, and require but little attention. When water is found to have accumulated, it is only necessary to open a small valve for a few minutes, when the water is discharged into the nearest sewer.

The total cost of the new subway, including land, buildings, stations, and rolling stock, was estimated at 550,000*l.* This, though a small sum when the circumstances of the route of the line are considered, is considerably more, probably, than a tramway of the same length &c. would have cost. The

electric railway has, however, advantages both in regard to quickness of transit and a terminal station having a central position in the City, such as a tram line would have little or no prospect of ever attaining.

In the stations, it may be added, each of the 10-foot 6-inch subways is opened into a larger tunnel, 20 feet in diameter, also circular in shape; these being arched in with brickwork, instead of with cast-iron segments. The centre line of one of the large tunnels is at a level about 10 feet below the other, so that passengers in proceeding to the low level platform pass below the upper one. The line was opened for traffic in December 1890.

The method of tunnelling described above proved most successful throughout, and was carried on with such speed that the contractors, working simultaneously at six faces, completed at times 100 feet of tunnelling per diem. Some delay was occasioned owing to the tunnels passing through the bed of an old watercourse near Stockwell. This was filled with sand and gravel under a 35-foot head of water, against which the shield already described was not a sufficient protection, and Mr. Greathead decided to use compressed air for this length. For this purpose compressors were erected, and the air was carried a distance of about 300 yards through a 6 inch pipe. The tunnels were driven under the normal air pressure to a point where the cover of clay was reduced to 5 feet, and from this point, the air locks having been erected, they were continued under compressed air. A small heading was driven at the top in advance of the shield, stout poling boards being used to support the top, resting at one end upon the forward end of the shield; the heading was then widened out, and the polings continued until about three-fourths of the circumference and the whole of the face had been poled. In an ordinary way the polings would not sufficiently prevent the outflow of air, but by frequent injections of lime grout under compressed air, through holes in the polings, the escape of air was much reduced. The two tunnels were driven in this manner under the large mains of the Lambeth and Southwark and Vauxhall Water Companies without causing the least disturbance. The speed attained under

compressed air in the gravel was at each face between 4 feet 6 inches and 5 feet per day.

The success of the City and South London Railway has caused other projects of a similar character to be brought forward in various other parts of London, some of which have already received Parliamentary sanction. The scope of the present work, however, will not permit of these being described in detail.

CHAPTER XXXVI.

TIMBERING OF THE AMPTHILL SECOND TUNNEL (MIDLAND RAILWAY).

THE widening of the Midland Railway between Kettering and London will be completed by the construction of a second tunnel at Ampthill, (40 miles) and another at Elstree, 12 miles from London. The new tunnel at Ampthill is 717 yards in length, and penetrates a hill the summit of which is 88 feet above rail level. It has been constructed entirely by means of three shafts sunk from the surface; the driving of a heading through between the faces was inadmissible, on account of the long cuttings in progress at each end of the tunnel, and of the treacherous nature of the ground on being exposed to the air.

The position of each shaft having been set out on the surface and indicated by pegs driven at four points, the sinking was proceeded with, the shaft being excavated to the outside diameter of the brickwork, 12 feet $4\frac{1}{2}$ inches. This diameter was closely adhered to, in order that as small a space as possible should be left between the finished brickwork and the ground behind.

Sections of the shafts in various stages of completion are shown in the diagrams (figs. 1 to 4, Plate XXXIII.). As the shafts were sunk, the sides were lined with poling boards 7 inches wide by $1\frac{1}{4}$ inches thick (figs. 2 and 3), closely packed all round, and supported by temporary curbs 3 feet apart. These were made up of 2 to 3 inch layers of pine sweeps, or segments, eight in each layer, the sweeps in the upper ring or layer breaking joint with those beneath. The outsides of the curbs were shaped to the curve of the shaft; and they were kept in position by 3-inch pine props, six

between each pair. When a depth of about 30 feet had been reached, a permanent curb was inserted. This was constructed of elm, which was found to be stronger and more durable than pine for the purpose. The brickwork was then built on this permanent curb, and was carried up to the top of the shaft, the poling boards, props, and temporary curbs being removed ahead of it. The solid ground, under the permanent curb, was excavated at six points around it, so as to allow of the insertion of strong 8-inch square pine props to support the brickwork; these were well wedged upon foot-blocks and raked back from it. By the same process the excavating, timbering, and lining for another length of shaft was proceeded with, the brickwork being carried up to the bottom of the finished portion above, and passing, for a height of $4\frac{1}{2}$ inches, in front of the curb supporting it. Between the last curb and the level of the bottom of the tunnel invert, a length of 33 feet, the shaft was very strongly timbered in a rectangular form, 10 feet square, with pine timbers, in order to support, for some time, the greater portion of the weight of the shaft above. This timbering was left in until the side length was completely excavated, timbered, and bricked. The brickwork of the shaft was 14 inches thick, and was enlarged to 18 inches for a height of 2 feet above the curbs. It was faced with specially radiated blue brindled bricks, the back-work being of ordinary red bricks. At three places the shaft lining was stepped out into bands 2 feet 3 inches thick, to serve as supports to relieve the 'eye' of the shaft of some of the weight above it; and to steady the shaft against lateral movement.

The lower part of the shaft having been securely timbered, the mining of the tunnel was commenced by the excavation of the side length of 12 feet next the shaft (fig. 4). In this length there were two faces to be timbered, the leading face and the face adjoining the shaft. About 8 feet below the top of the shaft timbering, a heading, 7 feet square, was driven for a length of 15 feet. This was timbered with head-trees 10 inches by 6 inches, placed 3 feet 6 inches apart, and supported by side-trees 6 inches in diameter. The sides and top of the heading were close poled with 7-inch by 1-inch boards, driven tight with wedges. When the heading

was finished, two crown bars, 16 inches in diameter and 19 feet long, one on each side of the centre of the heading, were placed in position; the head-trees and poling boards were left in above them, and the bars propped up temporarily by back props 9 inches in diameter. The heading was now gradually extended in width; the side-trees were removed until there was space for insertion of one more bar on each side, when this was propped in its turn.

These four bars were each now re-propped on leading 'nippers' 5 feet 6 inches long and 12 inches in diameter. A 'nipper-sill' was then laid in, and 'back-nippers' were propped from it to support the bars, all the nippers raking towards the length of the bars, and a back-prop 12 inches in diameter and 8 feet long being then inserted under each bar. The heading, thus widened, merged into the main excavation; and the mining of the length was continued, one more bar being put in on each side, followed by four 'liners' or ordinary bars. At this stage, the top sill, 14 inches square, made in two parts, scarf-jointed in the middle, and fastened together by a wooden key and iron straps, was drawn into place, a 'saddle' 12 inches by 6 inches and 12 feet long being placed on the top of the sill, and fastened to it by two iron straps. The six top bars or draw-bars were supported from the saddle by sill props, 10 inches in diameter. The other bars, except those near the sill ends, which were blocked up, were propped off the sill, all the props on the sill and saddle radiating out to the curve of the arched excavation. The sill liners or stretchers—which were placed one at each side and two in the centre—now followed, 12 feet apart, and were taken across to the corresponding sill of the other face timbering. The excavation of the clay now proceeded by picking and wedging only, no blasting being allowed on account of possible damage to the adjoining shaft.

When the middle sill level was reached, seven back-props 6 inches square were inserted, with slack-blocks 18 inches by 9 inches by 4 inches under each. These props were raked back from the position of the middle sill, their tops being let into the sill above, and the poling boards were closely packed behind them. Two more liners followed, and

the middle sill, similar to the top sill already described, was fixed in place, wedges and packings being tightly driven between it and the blocks under the back-props; tie pieces were also raked from the sill tops against the back-props. Eight vertical props, 6 inches square, were now put into position between the top and middle sills, those nearest the sides being under the ends of the top sill. An extra prop was added and raked up from the sill to support the 'liner' next below the top sill, a 'raker,' or angle strut being also fixed from the liner up to the nearest upright. The bar above the middle sill was propped from it, and secured by a wedge, driven between the bar and the sill prop next to it. The sill stretchers were then fixed to the sill opposite as before. Back-props, similar to the last, were now inserted under the middle sill; and when the sides were reached the bottom sill was drawn into position, the uprights between the two sills following. One more bar then followed on each side, being strutted off the sill and up to the top of the nearest sill prop. The sill stretchers were fixed in place, and the mining for the invert was proceeded with, no timbering being here needed, as the curve was shallow. Behind all the bars down to the middle sill, poling boards were fixed, those above the draw-bars being packed very closely, so that the ends butted up to each other at the centre of each bar, to prevent the boards being dragged with the bars, when these were drawn forward for the next length. The boards behind the other bars were not so closely packed, and their ends overlapped. Between the fourteen top bars, short stretchers 6 inches in diameter were fixed, about 4 feet apart, and two or three stretchers were inserted between the others. Numerous 'jack-pages,' 'driving wedges,' and 'slack-blocks' were used in fixing the work, as much depended upon tight work to make good the timbering. The bars were known by number, the two bars at the top being called 'crown bars,' the next on each side 'fourths,' and so on to the fourteenth bar, the even numbers only being used. The face timbering farthest from the shaft was left in until the excavation of the next length was ready at each level to receive it. The timberwork was the same for the two faces in the side length, except that at the face next the shaft, no props were used to support the crown bars at the top

sill level except those from a nipper sill laid in at the back and from the sill itself. The brickwork was then proceeded with. The side length was completed first, in order to give more room for the turning of the extra long 'shaft length.' All the material excavated, and that used in timbering and bricking the side length, was taken through a space less than 4 feet square in the shaft timberwork.

The side length being finished, the shaft length was prepared. This length (fig. 5) was 18 feet 6 inches long, and included in it the eye of the shaft. A heading was driven and the excavation proceeded, the material being taken out from behind each side of the shaft timbering, as well as the thin wall between the shaft and the side length. The face timbering was similar to that of the side length, but with the addition of two long sill rakers, 15 inches square, from the top and middle sills. They were bird-mouthed at the sills, being raked back and wedged up in an opening cut out in the brickwork of the side-length invert. The side timbering was somewhat different, on account of the greater length and weight to be supported. The liners at the sides were at one end wedged up against the brickwork of the side length, the draw-bars being packed up from the arch; at the face end of the length, the bars were propped from the sills in the usual way. Above the top sill, the bars were of a special length of 25 feet; there being no second or crown bars, the space which they would have occupied was taken up by the 'skip' in passing up and down the shaft. Between the fourth bars, which were kept apart by stretchers 6 feet long and 12 inches in diameter, and the permanent curb carrying the shaft lining, 'raker props' were inserted to bring the weight of the shaft down upon these bars. The original shaft timbering was gradually removed as the other timberwork took the weight of the shaft. Half of this weight was supported by the ends of the bars resting on the brickwork almost under the shaft; and half by an intermediate top and middle sill, props being fixed between them, and inserted also between the top sill and the bars. The lower of the two sills was supported by four props 11 inches square, blocked up from the invert bottom. These intermediate

sills were further strengthened by two long struts placed 10 feet apart, in the middle of each sill raked back to, and wedged up against the brickwork. The brickwork of the length was then put in, no iron curb being used for the eye of the shaft.

The running lengths (figs. 6, 7)—namely, the ordinary repeated 12-foot lengths—were, with some differences in detail, excavated, timbered, and bricked in a similar way to the side lengths. There was in these lengths only one face to timber; for at the other end was the brickwork of the last finished length, against which, as in the shaft length, the ends of the bars were fixed. Sill rakers were also used, but they were shorter than those already described. In the timberwork, the six bars at the top were drawing bars, those for every new length being drawn forward into the heading from their position on the top of the arch of the last length; and the spaces left by them between the brick packings were filled in with dry rubble. In order to provide the necessary space on the top of the arch for the drawing bars, the excavation was taken out 1 foot 9 inches higher than that required for the lining as far as the sixth bar, and was then tapered off to the exact dimensions for the brickwork at the springing of the arch. This vacant space, or 'sweeps,' on each side was tightly filled to the top with brickwork in mortar. As the excavation of each new length reached in turn the sill levels of the old face, the sills and the props from them were hauled over and re-fixed in position at the new face.

Most of the excavation in the running lengths was done by blasting, tonite in the form of candles with fuses attached being used, and long holes radiating towards each other being bored by hand to receive them. Six days were occupied in mining one length, and for this about 18 lbs. of explosive were used. Great care was taken that explosives should not be fired too close to the side walls, to prevent cavities being formed in them, as this would have endangered the safety of the work and also necessitated extra brickwork. During the mining and widening of the headings, the lumps of excavated material were thrown down into the

tunnel below, the men engaged in filling the trucks being protected them by a 'gate' of timbers strung together by chains.

The tunnel fronts are bell-mouthed, and were built before the cut had been completed. Manholes were built in the sides at a dis of 33 feet apart, and alternately on opposite sides of the tunnel. shafts remain as permanent ventilating shafts.

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CHAPTER XXXVII.

REMOVAL OF MILL OF ASH TUNNEL (CALEDONIAN RAILWAY).

An interesting piece of work was completed in 1892, by the removal of a long tunnel on the northern section of the Caledonian Railway, the work having been carried out without interfering with the traffic over the railway, which is the company's main line to the North. Several illustrations are given (Plate XXXIV.) which will enable the description of the operations to be followed with facility. Fig. 1 is a plan of the site of the tunnel; fig. 2 an elevation of the south end of the tunnel; fig. 3 a section near the centre; fig. 4 shows in detail the shield used in supporting the arch whilst in course of demolition from the outside; fig. 5 is a longitudinal section of the shield; and figs. 6 and 7 are sections of the top part of the shield, showing the screws by which the planking was driven close up to the inside of the crown of the tunnel.

The tunnel, it is interesting to note, was situated on the main line of the Old Scottish Central Railway, about six miles north of Stirling. It was made upwards of forty-three years ago, when the railway between Greenhill and Perth was constructed. The tunnel was 260 yards in length, the rails being on a curve of about three-quarters of a mile radius, and the gradient, 1 in 90, falling from north to south. It was 25 feet in width, and the height from rail level to crown of intrados varied from about 17½ to 20 feet (see figs. 2 and 3). At some parts of the abutment, the freestone rock showed solid, and had been dressed fair and straight on the face; but by far the largest proportion of the abutments were built of masonry, carried up to a height of about 4½ feet above the rails, from which

the brick arch sprung, this arch being of six brick rings equal to about $2\frac{1}{2}$ feet in thickness. The height from the crown of the arch to the surface above varied from about 30 feet at the lowest to about 44 feet at the highest part.

The arch having shown signs of weakness at some parts, it was decided to open it up; and, the necessary Parliamentary powers having been acquired, arrangements were made to carry out the work. There were about twelve acres of low-lying marshy ground, in a hollow close to the top of the tunnel (fig. 1), and arrangements were made with the proprietor to deposit the excavated material on this marsh, thus levelling it up. This allowed of all the material being excavated from above the arch without interfering with the traffic upon the railway. The dimensions of the tunnel being too small to admit of a shield, or centring under the arch sufficiently large to accommodate the ordinary double line working, the two lines of rails were drawn towards the centre and interlaced, a space of about 10 inches being left between the right-hand rails of the two lines, and of course the same space between the left-hand rails. This secured all the advantages of a single line, without the disadvantage of facing points or any movable parts. There was a permanent signal-box near the south end of the tunnel, and a temporary box was erected near the north end, the intervening space, 610 yards in length, being worked with the electric train tablet as a single line.

A movable iron shield was designed for the guidance of contractors, as shown on figs. 4 to 7, to be run under the brick arch whilst it was being removed, after the excavation was taken off the top. This shield, the construction of which is clearly shown in the illustration, was 21 yards in length, so that that length of arch could be dealt with at one time. Timbers were placed at each side of the tunnel, on which rails were laid to carry the flanged wheels, one pair under each rib, 9 feet apart, by which the shield was pushed forward (figs. 4 and 5). Being run into position under the arch, the shield was lifted by jacks till the top was against the brickwork; the bottom of the framing of the shield was then supported on timber blocks, keyed up so as to take all the weight off the wheels and

axles. The plates (see E E E, fig. 4), on which the timber cleading of the shield rested, were then raised by the adjustable screws, marked H H H, till the planks all bore hard on the woodwork. The plates E E E, fig. 4, were then blocked with timber on the arched rib to take the weight off the screws.

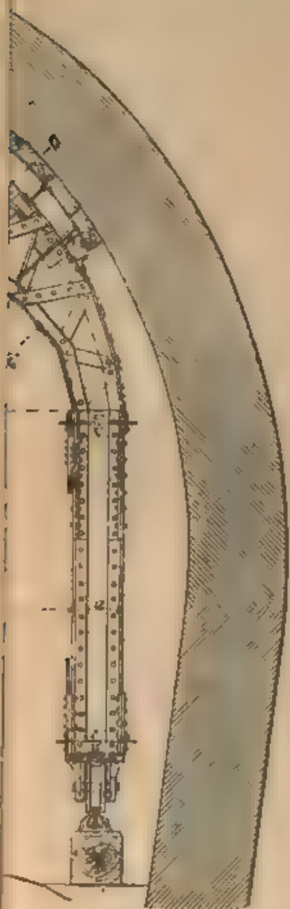
The shield was then ready for the breaking up of the arch at the crown, and removing the brickwork down to the top of the abutments. This done, the blocks were withdrawn from the top of the arched ribs, and the plates E E E lowered by means of the screws, figs. 6 and 7. The blocks under the shield were then removed, and the wheels lowered on to the rails, the shield run under the next length of the tunnel, and the same operations repeated till the whole length of the arch was removed, leaving the abutments to act as retaining walls for the bottoms of the slopes. The varying height of the arch presented a difficulty, there being several breaks in the roof, at some of which the versed sine of the arch varied as much as $2\frac{1}{2}$ feet. To meet this difficulty, the plates E E E, forming carriers for the timber cleading, were made in lengths of about 3 feet, with overlap slip points, fastened by bolts passing through slotted holes, but allowing sufficient play for the cleading being accommodated to the varying sections of the tunnel roof. The contractor constructed the shield as it had been shown on the drawing, and it was found to work very satisfactorily. It could be fixed up or moved about as required, without any interference with the traffic passing on the railway.

The contract was let to Mr. A. H. Boyle, contractor, Glasgow; and, besides the excavation and deposition of the materials (121,350 cubic yards), it embraced the erection of a bridge of 3 spans, with masonry piers and steel girders, to carry a road over the railway at the north end of the tunnel, the diversion of the road, and other contingent works. The excavation was begun at the north end of the tunnel, lines of temporary rails being laid from it to the site of the banking, along which the wagons were run by a pug engine. When sufficient space was cleared over the tunnel mouth, a steam digger was erected, which commenced work in August 1889. The excavations were at the same time carried on at

the higher places by 'dobbin carts,' and small wagons in advance of the digger, these reducing the surface level about 10 feet or 12 feet in height. The digger cut a gullet about 20 feet in depth over the centre of the tunnel the full length, from north to south and the width of the sweep of the arm, this portion of the work being complete in November 1889. It then made other two runs along the tunnel, widening out the excavation approximately the full breadth. When this was done, a different method was adopted. An inclined line of rails was laid from the surface level at the north, dipping down into the bottom of the excavations along the east slope, and was worked by a stationary engine, which hauled the wagons up by an iron rope. From the bottom of this incline, lines were laid to the north end of the tunnel and the materials excavated, laying bare the top of brick arch to about 7 feet under the level of the crown at the haunches. This method was carried out, until the excavations approached so near the south end that there was not room to work the wagons. A steam derrick crane was then erected on the top of the east slope at the south end, and the wagons hoisted by it from the bottom to the top of the excavation and run along the bank.

The excavation having sufficiently progressed to begin taking down the brick arch, the shield was erected and single line working began on October 12, 1890. Rails were laid above the arch, one on each side, to carry a movable staging, on which a derrick crane was fitted, by which the bricks were lifted as they were displaced from the arch and loaded into the trucks. On October 23 the brickwork was all removed from the first length of arch, 21 yards, and the shield moved forward and fixed under the second length, ready for the arch being broken. On November 1 the shield was moved forward under the third length, and so on until, on March 6, 1891, the last of the brick arch was removed. The iron shield was taken down and removed on March 22, and the rails relaid and double-line working resumed on March 29; but men were engaged till May 30 in removing rock and finishing slopes. The materials in the excavation varied very much from fine sharp sand to stiff boulder clay, with numerous boulders of different sizes, some so large that it was

PLATE XXXIV



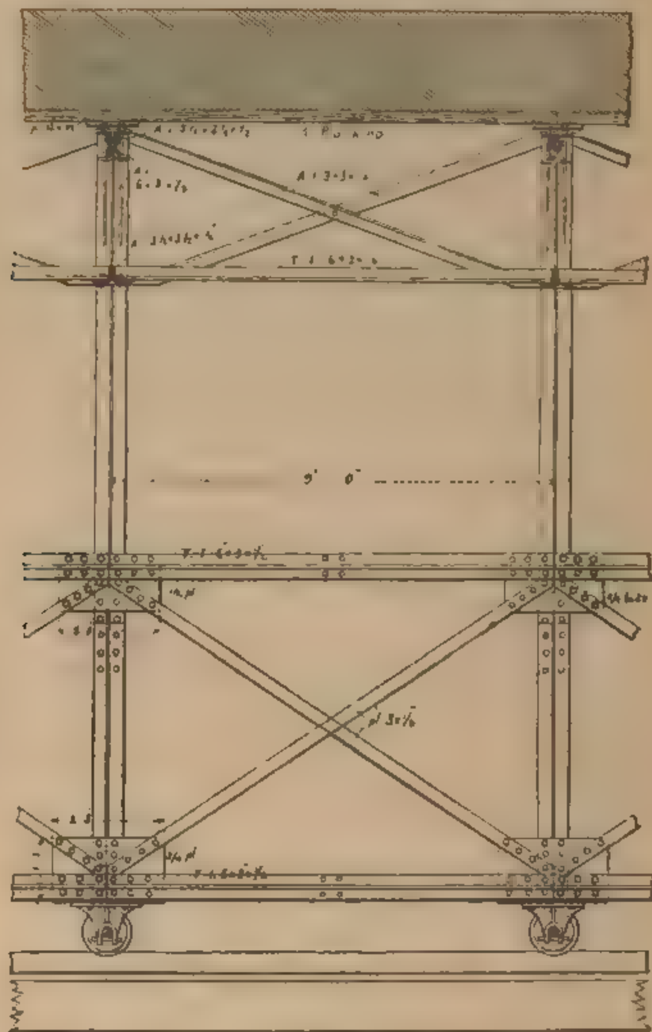


FIG. 5.

FIG. 6.—SECTION A B (FIG. 4). FIG. 7.—SECTION C D (FIG. 4).

Between pages 522 and 523.

necessary to blast them before they could be lifted. Rock, also, was encountered at some places, rising to a considerable height at the slopes. It was a soft freestone, some of the beds being thin, and all inclined at a somewhat steep angle, dipping from east to west. It was found necessary to remove some of this rock from the slope on the east side, for fear of slips. In some of the sand beds a good deal of water was met with, which was conveyed in drains down to the side of the line.

When the brick arch was taken down, the tops of the side walls were covered with concrete to an average thickness of 6 inches, projecting over the face and forming a coping against which the bottoms of the earth slopes were dressed. The cost of the work was about 10,000*l*. It was designed and carried out by Mr. T. M. Barr, M.Inst.C.E., Divisional Engineer of the Caledonian Railway.

CHAPTER XXXVIII.

THE ALIGNMENT OF TUNNELS.

THE setting out or alignment of tunnels may be classed under three heads: first, ranging or alignment above ground; secondly, the alignment below ground, either in a heading or in the full section of the tunnel; and thirdly, what may be termed the vertical alignment, or the transference of the surface line to the subterranean one. Should the tunnel be constructed without shafts, as in the case of the longest two existing at Mont Cenis and Mont Saint-Gothard, the vertical alignment is not required, as presumably the tunnel would be ranged from points observed directly from each extremity. In other words, the line of direction being given by the fixation of a couple of terminal points at any visible distance from the ends of the tunnel, the alignment may be obtained either by setting up the instrument, whether a plane transit or a theodolite, over the nearest point sighting backwards, reversing, and ranging forward, or by absolutely ranging the line backwards from the fixed points. It is extremely rare that the contours of the ground beneath which the tunnel is situated are sufficiently favourable to allow of one extremity being visible from the other; that is, to permit of the total length being ranged forward in either one direction or the other. The more general case is that in which, whilst the ends of the tunnels themselves are not sightable the one from the other, yet a summit level obtains from which, as a common point—even if, as frequently occurs, the ends are not visible—points in the direction of the line of trace can be accurately determined, marked, and rendered available for the alignment of the face headings or driftways. The distance at which these points are located from the mouths of the tunnels will depend upon the

physical features of the surface, but it is really a matter of little moment how far off they may be situated, so long as they are fairly within the range of the instrument employed. With this proviso, the farther off they are the better, as they admit of a more accurate and delicate adjustment by the cross wires of the telescope. In the Bletchingley Tunnel these terminal points were situated at a distance of two miles from the extremities of the tunnel, and consisted of small, solidly-built brick piers, painted black, with a white line in distinct relief upon them.

In setting out the Totley Tunnel (of the construction of which a full account has been given in Chapter XXVIII.), terminal points were also used. They were aligned by forward and backward sighting from a summit level, where an observatory had been built from which a view was obtained of a very extensive tract of the whole country. These two points were about 9,000 feet and 7,000 feet, measured horizontally, from the respective extremities of the tunnel. The distance of the same points from the summit observatory was over three miles, but by employing as a mark a board painted black, with a 3-inch white line on it, fitted with a plummet and fixed by guy ropes, and placing behind the board, at a few feet from it, so as to avoid shadow, a white calico screen, the mark could be distinctly distinguished so long as the sun was in front of the screen. These satisfactory results appeared to agree with those generally obtained in a similar manner. It is now well established, both by past and present experience, that for long distances white against black shows up best, and *vice versâ* for short distances. In the setting out of both the Totley and Cowburn Tunnels, the latter being on the same line of railway as the former, a black board, 2 feet by 1 foot 6 inches, faced with white cardboard, on which was drawn a broad arrow with varying widths of shaft, was levelled with a spirit level and supported from the back with light iron stays, and used for short distances.

At each of these two terminal points described, as well as at six other stations, placed where marked changes in the contours of the ground occurred, observatories were built for the location of the transit instrument used in aligning the tunnel. They were hollow, of brickwork in

cement, capped with stone, with a large flat cast-iron plate, having a hole 6 inches wide in the centre, let into the cap and run with cement, upon which the transit instrument rested. A brass scale of a width of $1\frac{1}{2}$ inches, and divisions of inches and twentieths, was fixed across the central hole in the plate, and a plumb line from the centre of the instrument could be dropped through the hole to touch the side of the scale. It may perhaps be questioned whether all these observatories are needed for a tunnel 6,229 yards, or a trifle over $3\frac{1}{2}$ miles, in length. It is, in fact, the opinion of some engineers that observatories are not required at all except for very long tunnels, and that strong permanent marks, over which a theodolite can be set up as often as is necessary, will answer every purpose for lining out and fixing the positions of the shafts. An inspection of the longitudinal section of the ground over the Totley Tunnel will indicate that the observatories on the eastern side of the summit limit serve principally for checking the lines run from the summit and terminal stations. The plane transit instrument is generally used for aligning tunnels, as it is less complicated, and requires fewer adjustments than the theodolite; though a slight drawback may be found in the necessity for removing the cross level every time the telescope is reversed, unless the operator is satisfied with one general levelling for each series of observations. A 6-inch transit theodolite by a good maker in the hands of a skilful and experienced engineer can be made to do anything and everything in connection with railway work with an accuracy, precision, and fidelity which leaves nothing to be desired. The use of the compass, even in mines, where this instrument has for so long been in use, is being rapidly discarded, preference being given, whenever practicable, to the ordinary theodolite.

As most tunnels are provided with shafts, the transference, or vertical alignment of the trace of the tunnel from above to below ground, is effected through them. The problem is to determine a vertical plane, perpendicular to the transverse axis of the tunnel, bounded by lines forming the surface and subterranean alignments, and connected at the points where the shafts occur by the vertical alignment, which may, therefore, be

regarded as so many ordinates. The simplest case is obviously where the vertical plane passes through the longitudinal axis—that is, where the shafts are ranged along the centre line of the tunnel. It should be mentioned that, so far as the simple alignment is considered, the words 'tunnel' and 'heading' are used in the same sense. Instances have occurred in which the shafts have been run parallel to the centre line of the tunnel, and in the tunnel at Mont Cenis shafts, which might more correctly be termed 'drifts,' were driven into the headings from the adjacent hill sides. A similar example occurred in the Clifton Tunnel, where a vertical alignment was set out from a station on the other side of the River Avon, through a horizontal gallery, ranged so as to intersect the centre line of the tunnel. The distance between any two consecutive ordinates in the vertical plane of alignment should be as great as possible, but, unfortunately, the diameters of shafts are generally of dimensions so limited as to restrict this length to about 8 feet or 9 feet, and often to a less amount. Exceptions sometimes occur, as in the well-known Box Tunnel, nearly two miles long, on the Great Western Railway, where some of the eleven principal shafts are 25 feet in diameter. A still more remarkable example may be found in the Kilsby Tunnel, which has a main shaft of 65 feet in diameter. Again, in the tunnel under the Hoosac Mountain in Western Massachusetts, which has a total length of $4\frac{3}{4}$ miles, the shafts are not all of a cylindrical form. Some are in the shape of parallelograms, 13 feet by 6 feet, others 14 feet by 8 feet, and one is elliptical, with major and minor axes of 27 feet and 15 feet respectively, of which the former is in the direction of the trace. In effecting the practical transference of the centre line down the shafts, the old methods have been either abandoned or partially employed under greatly ameliorated conditions. The apparatus employed for the Totley Tunnel consisted of a winding drum, upon which the wire was wound, mounted upon an iron frame, with a rachet and pawl to secure it in any position. The wire, which was weighted, passed over an adjusting screw, and was readily brought into line by turning the screw in either direction as required.

A few words may be added regarding the meeting of the separate

headings. It might be supposed, that the more numerous the shafts, and consequently the greater number of ordinates in the vertical plane of alignment, the less would be the divergence at the points of junction of the different headings; or of the different independent lengths of the centre line, supposing the tunnels to have no headings, as in the case of the Sydenham Tunnel. Experience, however, does not confirm this *primâ facie* rational and common-sense view of the subject, and a little consideration will explain the cause. Every separate operation, or every repetition of the same operation, is not only a source of error, but undoubtedly a cause of actual error, even if of an amount too insignificant to be appreciable. Consequently, every transference of the centre line is attended with some slight error, which, in the event of the position of any particular shaft not being sightable, either from the summit or terminal stations, and therefore requiring to be fixed by ranging from a previously determined shaft, might become cumulative. In the one case, the accuracy of the underground alignment depends upon that of a number of independent short lines which may or may not have been set out from the same fixed points; on the other hand, the centre line of the shaftless tunnel underground is ranged from each end from two unalterable terminal stations. The total

TABULAR STATEMENT SHOWING ERRORS IN ALIGNMENT AND IN LEVEL IN SOME OF THE MORE IMPORTANT TUNNELS OF THE WORLD.

Name of tunnel.	Length.	Error at junction.	
		Alignment.	In level.
	Feet.	Inches.	Inches.
St. Gothard	48,872	12·99	1·97
Mont Cenis	40,081	nil	12·00
Hoosac, Massachusetts	25,031	0·03	0·23
Ernst-August Adit Hartz (Division II.) .	23,760	1·20	0·09
Totley	18,687	4·50	2·25
Cowburn	11,106	1·00	—
Croton Aqueduct (Division I.) . . .	6,400	0·09	0·01
Nepean, N.S.W. (Division II.) . . .	4,341	0·42	0·25

deviation of the headings in the Totley Tunnel was $4\frac{1}{2}$ inches, or 1 inch in every 555 yards of heading. This is a very satisfactory result. In the Mont Cenis Tunnel, which is shaftless, the horizontal deviation is given as *nil*; but in the similar work in Mont Saint-Gothard the total error amounted to 13 inches, or 1 inch in every 627 yards, assuming the 'thirl' to have taken place about midway. In instituting this comparison, some additional credit may fairly be given to the St. Gothard Tunnel, having regard to its great length, which closely approximates to nine miles and a quarter.

CHAPTER XXXIX.

ROCK DRILLS.

The Optimus Rock Drill.—A drill to which this name has been given has recently been invented by Mr. P. J. Ogle. The principle of the drill is not absolutely new, but certain improvements have been introduced during the past two years which have gradually brought the working of the drill to its present state of efficiency. The drill is shown in use in fig. 1.

Fig. 1.

The Optimus Drill, the leading feature of which is its compound action, has been sold to Messrs. R. Schram & Co in consequence of the early recognition of its value which that firm bestowed on the invention—a recognition which has led to its adoption in supersession of their old drill, which has already rendered such excellent service.

The accompanying sectional drawings (figs. 2 and 3) will be sufficient to show the two pistons of unequal sizes which constitute the main feature of the machine. The air which has been employed to make the forward stroke, instead of being exhausted to the

atmosphere as hitherto, is utilised also for the backward stroke by being conveyed to the under side of the lower piston; a more powerful and rapid stroke is thus administered, in addition to an economy of compressed air being obtained. The saving is estimated by Mr. Schram to amount to 40 per cent. The two sections illustrate different types of drill, the principle being the same in both. The later form of the drill is that shown by fig. 2.

The operation of the drill is thus described. Assuming the piston valve *e* to be in the position shown in fig. 3, the cylinder *a* will be in communication with the air under pressure through the port *b*, the

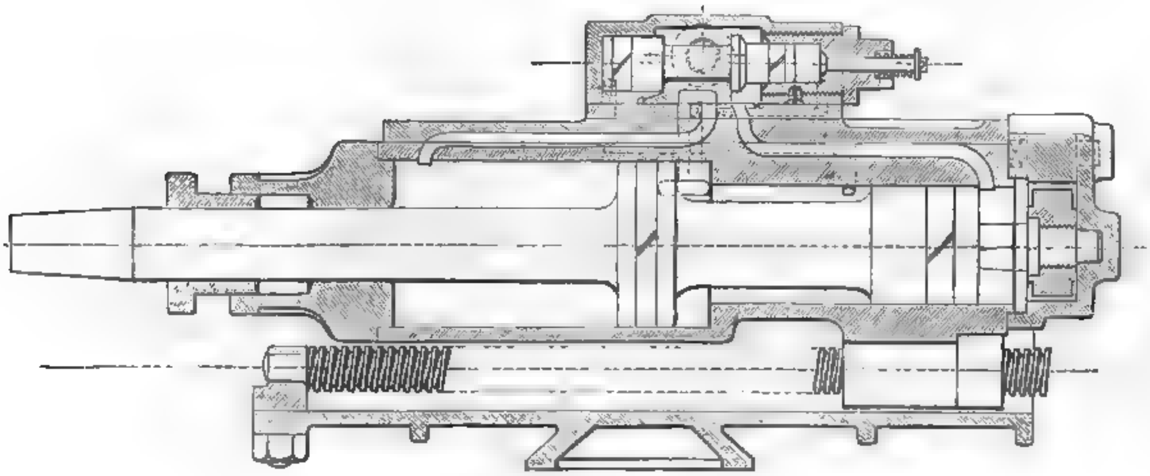


FIG. 2.

cylinder *a'* being at the same time in communication with the atmosphere through the ports *m*, *f*, *h*, the result of which combination is that the piston is forced forward and in its travel uncovers the port *d*, *d*, *d*. Through this port some of the compressed air passes into the small cylinder *r* behind the valve, and acting on a larger area than that which is subject to the constant pressure at *l*, there being no resistance, as the other end communicates with the atmosphere, pushes the valve over, cutting off the air-supply, and placing the cylinders *a* and *a'* in communication through the ports *b* and *m*. Then the air that has acted on the piston *c* now passes into the cylinder *a'*, where it acts on the larger piston, thereby moving it

back to its original position, the piston *c* at the same time uncovering the port *d* and placing the cylinder *r* again in communication with the atmosphere through the ports *d* and *h*, the constant pressure acting on the valve at *l* moving it over to the position shown in the illustration, and thus the action is repeated.

It will be seen that the air used for the forward stroke is again used for the backward stroke, without in any way impeding the piston in its forward stroke, and by its being admitted instantaneously to the cylinder *a*, whilst the cylinder *a'* is in free communication with the outlet, causes the piston to give a very powerful blow. At the end of each backward stroke there is still some pressure left behind the piston *c*, which, besides cushion-

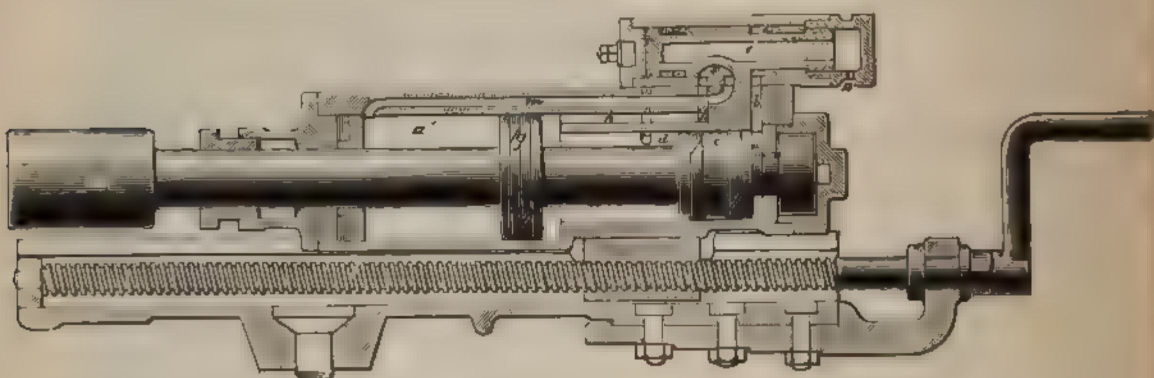


FIG. 3.

ing the piston, causes the space in the cylinder to be more quickly filled, thus causing a saving in air in addition to the increased power of blow.

An interesting trial of the Optimus drill was made against one of the old Schram drills, the rock operated upon being a block of Cornish granite. The points to be determined by the trial were, first, the relative depth of the holes bored in a given time; second, the consumption of air. The trial lasted one minute. The Schram drill, with 70 lb. air pressure, cut a hole $9\frac{3}{4}$ inches deep. In the same period the Optimus drill cut a hole $11\frac{3}{8}$ inches deep. In the test to show the air consumption—this also lasted one minute, both drill stocks delivering

blows on a log of wood—at the end of the stroke the Schram drill, with a pressure of air maintained throughout at 60 lb., took 175 charges of the air-compressor, the cylinder of which is 8 inches in diameter, by 12-inch stroke. The same pressure could not be maintained by the Optimus, as this drill, requiring only 90 charges of the compressor, took the air so slowly that the combined engine and compressor on wheels, when even working at 58 lb., showed a strong dislike to its surroundings by an evident tendency to leave them. The dancing of this machine could only be remedied by working the drill at 56 lb. pressure. When the air supply to the Optimus was cut off, the drill continued to work—without the tool, it may be mentioned—until the air pressure by the gauge fell to 17½ lb., thereby furnishing another proof of the much reduced supply of air requisite. The drill shown in the diagram has a diameter of 3¼ inches, and a stroke of 6½ inches.

Comparing the weights of the two drills, it will be found that the Optimus is somewhat heavier, as it weighs 295 lb., or 75 lb. more than the Schram drill. It should, however, be remembered that the new drill has a stroke 1 inch longer than the old type. The drills are manufactured for Messrs. Schram & Co. by Messrs. J. I. Thorneycroft & Co.

The Hirnant Drill.—With reference to the Hirnant drill, which has been referred to in the earlier part of this work in connection with the construction of the Cowburn and other tunnels, Messrs. Larmuth & Co., the patentees, state that the most rapid boring which has been accomplished by this drill was performed in the Moorhouse Tunnel of the Thirlmere Water Scheme. In the presence of the Manchester Water Committee, this drill pierced eighteen holes, each 4 feet 6 inches deep by 1½ inches diameter at the end, in three hours thirty-five minutes. This was performed by two 3½-inch cylinder Hirnant drills mounted on a carriage, and the time above given included two changes of drill-bits to each hole and the shifting of the drills on the carriage for various positions on a face 8 feet 9 inches wide, by 7 feet 3 inches high. This performance is one which has probably never been equalled.

CHAPTER XL.

THE VENTILATION OF TUNNELS.

DURING the early days of the working of the St. Gothard Tunnel, when it was uncertain whether the natural ventilation would be sufficient to remove the impure air and products of combustion, or whether it would be necessary to resort to artificial means of ventilation, a series of temperature observations were made by placing thermometers in the fifteen refuge chambers within the tunnel. These were observed every eight hours by the watchmen in the tunnel, and the results recorded. The strength and direction of the air-currents, and the density of the smoke, were at the same time noted, the external atmospheric conditions being simultaneously recorded at the meteorological stations at either end of the tunnel. An abstract of the results obtained from 1883 to 1888 is appended; from these it appears that the maximum temperature obtained in chamber No. 8, in the middle of the tunnel, has been practically constant (22°·8 to 23°·4 Centigrade), whilst the annual minimum shows a small but continuous diminution from 16°·4 in March 1883 to 16°·0 February 1884; 15°·0 February 1885–86; 14°·8 December 1887; 14°·5 January 1888.

Before the joining of the headings in February 1880, the mean temperatures were, in the Göschenen end, 26°·6 and 29°·6 Centigrade; and in that of Ariolo, 29°·2 and 31°·6 Centigrade respectively.

The mean rock temperature of the entire length of the tunnel was originally 23°·43; the mean air-temperature February 29, 1880, 21°·60; on February 11, 1881, 19°·3; and on February 11, 1882, 14°·2.

These figures show very clearly the diminution in the mean natural temperature of the whole tunnel.

As regards the movement of the air, the observations were confined to

noting the direction of the current and estimating its strength, which was registered respectively as strong, moderate, weak, or calm. The natural draught through the tunnel, and which, in fact, ventilates it, results from the differences of the air pressures at either end, the wind blowing from the side of highest pressure, and its strength being proportional to the square root of the differences of the two pressures. The column of 36 metres due to the difference in the relative level of the two ends being sometimes in favour of, and at others in opposition to, the prevailing wind, according to whether it is lighter or heavier than the external air. The combined effects of differences in temperature and moisture at the two ends resulted, during the five years' observations, in the following average distribution of the air-currents, the draught being either continuously north or south for some time, or changing from one direction to the other at short intervals.

Years.	Days of prevailing North wind.		Days of prevailing South wind.		Days with alternating North and South winds.	
	Winter.	Summer.	Winter.	Summer.	Winter.	Summer.
1883	70	75	45	29	66	80
1884	60	82	56	42	67	59
1885	51	80	64	33	67	68
1886	55	70	60	54	67	59
1887	65	79	45	40	72	64

The period from October to March is included in 'winter,' and from April to September in 'summer.'

It would appear from these results that the prevailing external winds at the tunnel stations have no effect upon the duration or strength of the current within the tunnel; nor does the influence of a passing train, acting as a piston, appear to be more than local and unimportant.

From the results of the smoke observations recorded, it appears that for only a very few days throughout the year is the middle of the tunnel entirely free from smoke; but, on the other hand, the number of entirely smoky days at that point is much fewer than at the ends of the tunnel.

The tunnel is found to be in the most unfavourable state on those days in which the wind is only slight, or is unsteady in direction.

The work necessary for repairs, maintenance of way, &c., is, as far as possible, confined to days of strong prevailing winds in one direction, or to the night time, when only two express trains pass through the tunnel, and the smoke is least noticeable. The six years of observation have proved that the natural ventilation of the tunnel proceeds practically continuously either in one direction or the other.

Ventilation of Mont Cenis Tunnel.—The ventilation of Mont Cenis Tunnel is effected by means of a mechanical contrivance which forces air, under pressure, through pipes laid along the tunnel. The pipes are provided at intervals with cocks, so that if a man working at any point in the tunnel suffered inconvenience from bad air, he could open a cock, and thus surround himself with a fresh and pure atmosphere. An exhausting apparatus is also provided at one end of the tunnel for the purpose of drawing the air out. Neither of these provisions has, however, been found very effectual in practice, and in reality the tunnel in a great measure ventilates itself. One half of the tunnel being built on a steep rising gradient, and a current being produced, owing to the air being heated by the passage of the locomotives, this part of the tunnel acts as a sort of shaft or chimney which ventilates it throughout. That the ventilation is effectual is demonstrated by the fact that it is frequently possible from one end of the tunnel to see the opening at the other end immediately after engines working at full speed have passed through it.

No action of this kind, however, is observable in the St. Gothard Tunnel, which is practically level from end to end, the incline being only sufficient for drainage purposes. Fortunately, however, one end of the tunnel is in a warmer climate than the other end, and there is therefore, as a rule, a draught through the tunnel which, as already shown, serves for purposes of ventilation.

The Orayu Tunnel.—The summit tunnel on the Orayu Railway stands at such a height above sea level that to breathe even pure air requires painful exertion. Its length is $\frac{3}{4}$ mile, one half of this distance being on a

gradient of 1 in 27, preceded by an approach of 1 in 25 on a curve. The tunnel was for a single line only, and the use of coal-burning locomotives was most distressing to passengers. The unpleasantness has now to a great extent been mitigated by the use of petroleum as fuel, the locomotives being adapted for the latter without difficulty.

Usui Railway Tunnels.—The ventilation of the tunnels on the Usui Railway (Japan) has been a very serious question to the responsible engineers. The tunnels are 26 in number, 2·76 miles in a total distance of a little over 4 miles. The atmospheric conditions in these tunnels were very trying to those on the engines, the immediate cause being the intense heat of the air, caused by the great volumes of steam discharged from the four cylinders of the Abt engines used on the line. These four work simultaneously and almost without expansion, and, added to other products of combustion discharged from the chimney, the feeling produced on the uncovered parts of the body was one of acute pain, and to this is added the necessity of inhaling the heated atmosphere. The train on entering the tunnel acted as a plunger or piston, driving the air before it; the exhaust steam was discharged against the tunnel roof, and enveloped the engine in smoke. The vacuum, caused by the train entering the tunnel, was filled with the air following the train into the tunnel; this volume of moving air being increased as the train proceeded, and, being aided by the incline of 1 in 15 and the condensation of the steam from the engine, it eventually drove the smoke beyond the engine and the carriages. To avoid this, a canvas curtain was pulled across the mouth of the tunnel directly after the train had entered it. The vacuum was then filled with air from the front of the train, thus keeping the smoke behind the engine. This arrangement was found to act in a more satisfactory manner than any other appliance which had been tried.

Ventilation of Hoosac Tunnel, U.S.A.—The Hoosac Tunnel, which is about $4\frac{3}{4}$ miles long and perfectly straight from end to end, is ventilated entirely by a natural current of air through a central shaft.

The two extremities of the tunnel are at the same elevation, being 769 feet above sea-level; but from each end to the central shaft there is a

rising gradient of 26·4 feet to the mile (equal to 1 in 200). The shaft is elliptical in shape, being 27 feet by 15 feet, and 1,028 feet deep from the ground surface to the floor of the tunnel. When the tunnel was first opened for traffic, it was laid for a single line of rails only, and timber shields were placed at the foot of the shaft to protect the passing trains from the danger of stones being dislodged from the sides and falling on the line. In 1882 the increased traffic necessitated the laying of a second line of rails, which also required to be protected. As the ventilation of the tunnel would have been seriously impaired by the introduction of additional timber shields, the plan was adopted of closing the tunnel at the bottom of the shaft, and building two spiral ventilating galleries, 15 feet in diameter, starting at right angles to the line of railway from opposite points in the tunnel. Each of these was 42 feet from the centre, and wound up to a height of 70 feet before entering the main shaft. The combined areas of the two galleries being greater than that of the shaft, they maintained the ventilation of the tunnel, fifteen minutes sufficing, under ordinary circumstances, to clear the shaft and renew the air of the tunnel from end to end.

The maximum number of trains traversing the Hoosac Tunnel in 1889, with an average of 30 cars each, was sixty-five, which closely approximates to the limit which could be safely run under existing conditions. If the traffic is to be still further increased, it will probably be necessary to have recourse either to artificial means of ventilation or to a different type of motor to the ordinary locomotive engine.

The St. Louis Tunnel.—This tunnel is constructed beneath the city of St. Louis, and is 4,095 feet in length. The two main portions run nearly at right angles to each other, and are connected by a curve, about 740 feet in length, in the centre of the tunnel where the ventilating fan is placed. The steepest gradient is 1 in 75. It is practically a double tunnel; for a central wall, with openings at a distance of every 25 feet, separates the two lines of rails throughout, excepting where the fan is placed, and at the Custom House. Originally air holes were made at various places in the roof of the tunnel, in the expectation that they would suffice to keep it

free from smoke and foul air. This, however, proved to be erroneous, added to which, constant objections were raised to the smoke being allowed to issue into the streets at ground level.

These openings were, therefore, eventually closed, and a central fan and ventilating stack substituted.

The stack is of boiler iron, 130 feet high, 37 feet diameter at the base, and 15 feet at the top. The fan, which is 15 feet in diameter and 9 feet wide, consists of a pair of steel cones placed butt to butt and riveted together. These cones carry 16 blades, 3 feet wide, driven by an engine of 190 horse-power, at a speed varying from 70 revolutions per minute when the passenger traffic is light, to 110 revolutions when it is heaviest. At 110 revolutions the tunnel is cleared of smoke in four and a half minutes from the time of the locomotive passing the fan when going east, and in three and a half minutes when going west; and it has been estimated that the total amount of air requiring to be removed on the passage of each train is 2,750,000 cubic feet. This estimate would, however, appear to be excessive, as, from tests made by Mr. N. W. Eayes, M.Am.Soc.C.E., it would appear that the volume of air driven up the shaft does not exceed 240,000 cubic feet per minute when the fan is running at 110 revolutions.

The ventilation of the tunnel, on the whole, appears to be fairly effectual; although it is noticed that when strong westerly winds prevail the air in parts of the tunnel is foul, and that in certain states of the atmosphere the smoke moves sluggishly.

In 1888 the average interval between the trains was eight and a half minutes; but in 1890 the traffic was so increased that for several hours in the day trains passed through the tunnel at the average rate of one in every four minutes.

Postscript as to Tunnelling on Mountain Railways.—*Protective Works.*—In the construction of works of this description special pre-

cautions are necessary to guard the entrances against dangers which are almost unknown in connection with tunnelling in the lowlands. Consideration must be given to the destructive effect of torrents or freshets, which frequently dislodge large masses of material; to the risks of landslips, more especially peculiar to treacherous loose formations of the soil; and to the dangers and delays produced by avalanches and heavy snowfalls. Various means of defence are employed to combat these difficulties, which vary according to circumstances. In some cases, works are carried out high up the mountain sides. These consist either of stone walls or barriers of wood, or more frequently of wood and wattle work. The walls are distributed in short lengths over the ground, having their sides at right angles to the probable direction of the anticipated danger. The best protection against avalanches is, however, afforded by woods, generally of fir trees; but in many places these are not practicable, owing either to the hillsides being too steep or stony, or to the elevation being too high to permit of the growth of trees. Instances have occurred in the Himalayas, however, of huge avalanches cutting tracks 50 to 60 feet through the mountain forests, and depositing at the bottom of the valleys piles of shattered tree trunks 30 feet high or more. Forests, therefore, though a good, are not an absolute safeguard against the effects of avalanches, even where the circumstances permit of their being cultivated for the purpose. In the Rocky Mountains snowsheds, often very strong and expensive to construct, are erected.

Cost.—The cost of Alpine tunnelling has of recent years been considerably reduced. The first tunnel—the Mont Cenis—cost about 143*l.* per yard; the St. Gothard Tunnel 103*l.*, and the Arlberg only 85*l.* per yard. It is anticipated that the Simplon Tunnel will cost still less. The reduction does not appear to be due to the greater facility offered by the strata that were pierced, but rather to the greater rapidity of execution brought about by improvements in the machinery used.

GLOSSARY.

ADIT. *See* HEADING.

ALIGNMENT. *See* RANGING.

BARS. Strong timbers, or trees of considerable size, placed horizontally, for supporting the poling boards by which the faces of the excavation for the tunnel are supported. The CROWN-BARS support the upper part of the excavation; the SIDE BARS the lateral portions.

BENCH, BENCHING. A ledge left on the edge of a cutting in earth or in rock.

BREAK-UP. An excavation commenced from a bottom heading and carried upwards, so as to form two interior working faces.

BROB. A wrought-iron spike driven into bars or sills, around the ends of props, to steady them.

CURB. A suitably formed ring of brickwork or of cast iron, at the base of a shaft, surmounting a circular orifice in the roof of the tunnel. A DRUM-CURB, sometimes used in course of construction, is a flat ring for supporting the brickwork, forming a portion of a cylinder of cast iron, having the same diameter externally as the shaft of brickwork. Temporary curbs of oak are also used.

DOG. An iron holdfast, or piece of round iron, with pointed ends bent at right angles.

DRIFT. *See* HEADING.

FACE. The surface exposed by excavation. The WORKING FACE, or FRONT, or FOREHEAD, is the face at the end of the heading; or at the end of the full-size excavation.

FOOT BLOCKS. Flat pieces of wood placed under props, to give a broad base, and thus prevent the superincumbent weight from pressing the props down.

FOREHEAD. *See* FACE.

FRONT. *See* FACE.

GALLERY. A drift or adit. ADVANCED GALLERY (French), the heading for the tunnel.

GETTING IN THE TOP. Cutting out and timbering the crown of the excavation for the tunnel.

GROUND MOULDS. A portion of the LEADING FRAMES.

HEADING. A small horizontal mine, driven in advance of the full-size excavation; or, it may be, laterally, to join the tunnel. In earth or in loose rock, it is constructed with SETTINGS or HEADING-FRAMES at intervals, cased in POLING BOARDS. It may be a TOP HEADING or a BOTTOM HEADING. A CROSS HEADING, or a SIDE DRIFT, is a communication from a side shaft to the tunnel. An ADIT or DRIFT usually leads to or from a tunnel; but the word HEADING is usually employed to signify the excavation in advance of the tunnel.

INVERT SKEWBACKS. The planes in which the curves of each side wall meet those of the invert.

LENGTHS. The successive sections in which a tunnel is executed. SHAFT-LENGTHS are directly under the working shaft; SIDE LENGTHS are on each side of the shaft-length; LEADING LENGTHS are prolongations of the tunnel from the side lengths; JUNCTION-LENGTHS are the lengths which complete the portion of the tunnel extending between two shafts, or between a shaft and an entrance.

LEADING FRAMES. Formed to the contour of the invert and the walls, to guide the bricklayers.

POLINGS, POLING BOARDS. Planks or deal-ends, by which the surface of an excavation may be *poled* or planked. Sometimes the work is called *close-poling*.

PROPS. Struts or posts, either vertical or raking, usually of round timber, used as supports, or as stays. Raking props are sometimes called RAKERS.

RAKERS. *See* PROPS.

RANGING. Laying out the line of the tunnel.

SETTINGS. *See* HEADING and SQUARE TIMBERING.

SHAFTS. Pits sunk from the surface. TRIAL SHAFTS are made to ascertain the nature of the strata to be excavated. WORKING SHAFTS give access to a tunnel in progress of construction, for moving material up and down, pumping up water, and ventilation. PERMANENT SHAFTS admit light, and act as ventilators when the tunnel is completed.

SILLS. Strong timbers of large scantling, placed horizontally across the line of the tunnel, to support the props, bars, and other portions of the timbering.

SHAFT-SILLS support the shaft above the arch, when the ground is solid.

SQUARE TIMBERING. The formation of a shaft through an excavation. It consists of SQUARE SETTINGS or frames at intervals, close-poled behind.

SUMP. A cavity like a cesspool or well sunk or built into the ground, usually at the bottom of a shaft, to receive and collect water, which is removed by means of buckets, barrels, or pumps. SUMPING is the collecting of water by means of a sump.

THIRL, THIRLING. The meeting of workings approaching each other in opposite directions.

TIMBERING. The timber structure employed for supporting the faces of the excavation during the progress of construction.

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PRINTED BY
SPOTTISWOODE AND CO., NEW-STREET SQUARE
LONDON